Optimal Capacitor Placement in Distribution Systems using Heuristics Techniques

by

Ali Hasan Yasin Al-Mohammad

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

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This thesis, written by

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عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

This Thesis is dedicated to my

Father

Mother

Brothers *Tawfiq, Sami, Yasin and Mohammad*

Sisters

Beloved wife

Sons *Hasan and Mohammad*

and

Daughter *Fatimah*

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All praise is for Almighty Allah for having guided me at every stage of my life. Acknowledgement is due to King Fahd University of Petroleum and Minerals for providing support for this work.

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Abstract

Name : Ali Hasan Yasin Al-Mohammad

Title : Optimal Capacitor Placement in Distribution Systems Using Heuristic Techniques

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It is a well-known fact that installation of capacitors in power systems, especially at the distribution levels, results in considerable economical benefits. However, the extent to which these benefits are achieved depends on how the capacitors are placed on the system. Due to this, optimization of the capacitor placement problem (CPP) becomes of a great significance. The CPP is combinatorial in nature. When dealing with a real-world problem of a reasonable size, exact optimization algorithms become impractical to apply to solve the CPP as they require a tremendous amount of time to converge. Therefore, it is necessary to have effective heuristic techniques in order to obtain the optimal solution to the CPP in a reasonable amount of time and with minimal computing resources. This thesis investigates the implementation of various heuristic techniques for solving the capacitor placement optimization problem. Simulated annealing, genetic algorithm, tabu search and a hybrid algorithm formed by combining both genetic algorithm and simulated annealing are all used as heuristic optimization tools. An improved capacitor placement optimization model is formulated. The effect of nonlinear loads on the optimal solution is studied. The proposed solution methodologies are implemented in FORTRAN-77 and tested on a 69-bus radial distribution system and a 30-bus distribution system containing a loop. Computational results obtained showed that the heuristic techniques are capable of producing high-quality solutions in a reasonable computation time.

Master of Science Degree
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خلاصة الرسالة

اسم الطالب : علي حسن ياسين المحمد

عنوان الرسالة : الوضع الأمثل لمكثفات القدرة في أنظمة التوزيع الكهربائية باستخدام الطرق التنقيبية

التخصص : هندسة كهربائية

تاريخ الشهادة : مايو ١٩٩٩م

من الحقائق المعروفة أن تركيب مكثفات القدرة في الأنظمة الكهربائية وخصوصا في شبكات التوزيع يؤدى إلى الحصول على فوائد اقتصادية كبيرة. ولكن مدى الحصول على هذه الفوائد يعتمد على الطريقة التي يتم بها تركيب هذه المكثفات من حيث الموقع و السعة و عدد و نوع المكثفات المراد تركيبها. ولهذا فقد اكتسبت مشكلة إيجاد الوضع الأمثل لمكثفات القدرة في أنظمة التوزيع أهمية بالغة. إن استخدام طرق البحث الشامل أو المستنفذ لحل هذه المشكلة أمر غير عملي نظرا للوقت الطويل الذي تتطلبه، ومن أجل الحصول على حلول مثالية بوقت معقول وبأقل قدر من العمليات الحسابية فانه ينبغي استخدام الطرق التنقيبية.

تهدف هذه الرسالة إلى استخدام الطرق التنقيبية لإيجاد الوضع الأمثل لمكثفات القدرة في أنظمة التوزيع، ومن هذه الطرق طريقة محاكاة التلدين وطريقة النظرية الجينية وطريقة بحث المنع بالإضافة إلى طريقة هجينه مكونة من الطريقتين الأوليين.

في هذه الرسالة تم الآتي:

- عمل نموذج رياضي مطور لمشكلة إيجاد الوضع الأمثل لمكثفات القدرة في أنظمة التوزيع
- عمل برامج بلغة الفورتران للحصول على الحل الأمثل للمشكلة باستخدام الطرق التنقيبية المذكورة
- دراسة تأثير الأحمال غير الخطية على الحل الأمثل
- تجربة البرامج على نظام توزيع إشعاعي ونظام توزيع يحتوي على بعض الدوائر الحلقية

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

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Chapter 1

Introduction

This introductory chapter contains six sections. Section one highlights some of the capacitor functions in power systems. The capacitor placement problem is defined in section two. While section three introduces the heuristic optimization techniques, section four discusses the power system harmonics. Thesis objectives are presented in section five. Finally, section six explains how the thesis is organized.

1.1 Capacitor function in the power system

The application of shunt capacitors in distribution systems has always been an important subject to distribution engineers. It is a well-known fact that the major portion of the power losses occurs at the distribution level. The cumulative data gathered for the whole utility industry indicate that about 60% of the capacitors is applied to the distribution feeders, 30% to the substation buses and the remaining 10% to transmission system.

Shunt capacitors have been widely installed by utilities to provide reactive power compensation to improve service quality via voltage regulation, to improve the efficiency of power distribution via real power and energy reduction and to achieve deferral of construction, if possible, via system capacity release.

The economic benefits which can be derived from capacitor installation can be summarized as:

1. Released generation capacity.
2. Released transmission capacity.
3. Released distribution substation capacity.
4. Reduced energy losses.
5. Reduced voltage drop (Improved voltage regulation).
6. Reduced capacity of feeder and associated apparatus.
7. Postponement or elimination of capital expenditure due to system improvements and/or expansions.
8. Revenue increase due to voltage improvements.

The extent of these benefits depends on how the capacitors are placed on the system. Due to this, optimization of the capacitor placement problem becomes of a great necessity.

1.2 Capacitor placement problem (CPP)

Recently, the growing need for distribution automation and control has generated interest in the capacitor placement problem. In fact, capacitor placement is regarded as a function with outstanding importance associated with distribution automation.

The general capacitor placement problem (CPP) is defined as the problem of how to determine the location, type, number and size of capacitors to be installed in the system. The objective is to minimize the energy losses while considering the capacitor installation costs. In other words, the revenue savings resulting from the energy loss reductions are weighed against the installation cost of capacitors. The goal is to achieve the optimal or maximum value while satisfying the system constraints.

The decision variables of the CPP are discrete i.e. the solution is a set of integers and therefore, CPP is classified as a combinatorial problem. The problem of finding optimal solutions to such a problem is therefore known as combinatorial optimization.

1.3 Heuristics

A naive approach to solve a combinatorial optimization problem is simply to list all the feasible solutions of the given problem, evaluate their objective functions, and pick the best. However, it is immediately obvious that this approach of complete enumeration is likely to be grossly inefficient. In addition, although it is possible in principle to solve any problem in this way, in practice it is not due to the vast number of possible solutions to any real-world problem, such as the general CPP in distribution systems, of a reasonable size.

Heuristic techniques are used as a contrast to complete enumeration methods which guarantee to find the global optimum. The term heuristic is derived from the Greek heuriskein meaning to find or discover. A heuristic is a technique seeking good (near-optimal) solutions at a reasonable computational cost without being able to guarantee optimality, or even in many cases to state how close to optimality a particular feasible solution is.

Another argument in favour of using heuristics is that they are more flexible and more capable of coping with more complicated (and more realistic) objective functions and / or constraints than exact algorithms.

1.4 Power system harmonics

Nowadays the levels of harmonic voltages and currents on distribution systems are becoming a serious problem. Harmonics can cause a lot of operational problems. Some of these problems include the following:

1. Capacitor bank failure from dielectric breakdown or reactive power overload.
2. Interference with ripple control and power-line carrier systems.
3. Excessive losses in and heating of induction and synchronous machines.
4. Overvoltages and excessive currents on the system from resonance to harmonic currents or voltages on the network.

5. Dielectric instability of insulated cables due to harmonic overvoltages.
6. Inductive interference with telecommunication systems.
7. Errors in induction watt-hour meters.
8. Signal interference and relay malfunction, specifically in solid-state and microprocessor controlled systems.
9. Interference with large motor controllers and power plant excitation systems.

Loads that do not draw a sinusoidal current from a sinusoidal voltage source are said to be nonlinear, that is the relationship between voltage and current at every instant of time is not constant. Examples of nonlinear loads include rectifiers, welders, inverters, arc furnaces, frequency converters and voltage controllers. Nonlinear loads are one of the major sources of power system harmonics. They generate excessive harmonic currents that can result in unacceptable voltage distortion levels.

The degree to which a power system is affected by harmonics depends on the harmonics source, its location on the power system and the network characteristics promoting propagation of harmonics. Capacitor bank sizes and locations are significant factors in a distribution system's response to harmonic sources. The combination of the system reactance and capacitors causes both series and parallel resonant frequencies for the circuit. Due to these resonant conditions, the total harmonic distortion is magnified to unacceptable levels.

Relocation & resizing of capacitors could shift resonance to other non-disturbing frequencies. However, this may reduce the net savings of capacitor installation. Therefore, when solving the optimal capacitor placement problem, harmonic currents injected by the non-linear loads shall be considered in the problem formulation in order to assure that the optimal solution obtained does not result in excessive harmonic distortion.

1.5 Thesis objectives

The objectives of this thesis are listed hereunder:

1. To present a comprehensive and an extended formulation for the CPP in distribution systems that takes into consideration more practical and more realistic constraints.
2. To solve the general CPP in distribution systems using various modern heuristic techniques, namely simulated annealing, genetic algorithm, tabu search and hybrid algorithms and to compare the results obtained by these methods.
3. To study the effect of nonlinear loads on the optimal solution of the CPP in distribution systems.

1.6 Organization of the thesis

The thesis contains a total of six chapters. Chapter two contains the literature review. System modeling and problem formulation are presented in chapter three. Chapter four discusses different solution methods used to solve CPP, namely simulated annealing, genetic algorithm, tabu search and a hybrid algorithm formed by combining both simulated annealing and genetic algorithm (henceforth: GA-SA algorithm). In chapter five, simulation results obtained from each one of these methods are presented. Finally, conclusions and suggestions for future work are given in chapter six.

Chapter 2

Literature Review

In this chapter, the literature on capacitor placement optimization problem is reviewed. In addition, scope of the work carried out in this thesis is summarized.

2.1 Review of previous work

Several research papers and reports addressed the subject of optimal capacitor placement in distribution systems. The followings present a brief review of the work undertaken so far.

Kaplan presented a computerized trial and error heuristic method for optimizing the present worth of revenue savings [1]. The savings are associated with released system capacity and the energy loss reductions. The non-uniform load distribution and conductor size were taken into consideration. Both fixed and switchable capacitor banks and their installation cost were also considered. The availability of the capacitor banks in accordance with the standards and released capacity cost were included as well. The effects of the main and the lateral branches were studied.

The optimization process consists of three major steps. First is the choice of the location and type for the smallest standard size bank. The program scans all feeder branches moving along the branch toward the substation. Second is the improvement of the solution considering the standard bank size. The aim of this step is to increase the objective function. Third is the selection of the type of control for switched banks.
The method, however, does not consider system voltage limitations or the economic effect of voltage rise resulting from capacitor applications.

S. Rama Iyer et al defined the objective function of the optimal capacitor placement problem as a maximization of revenue savings resulting from power loss reduction [2]. The objective function is maximized while considering the capacitor installation cost. The objective function is solved by a mixed-integer programming technique subjected to the following constraints:

1. Upper and lower limits of generator voltage magnitudes.
2. Upper and lower values for the transformer tap settings.
3. Upper limit on the number of units in each capacitor bank due to technical reasons such as switching voltage surges.

The proposed method finds the optimal location of a capacitor by the coordinated variation of generator voltages, transformer tap settings and the number of units in each capacitor bank. The method has some features which result in considerable savings in computer time and memory. First is the elimination of dependent variables in the problem formulation. Second is the decomposition of the problem into two smaller sub problems. Third, is the avoidance of the load flow calculation.

A. A. El-Kib et al presented a new model for radial distribution systems in [3]. The model considers asymmetrical and multi-grounded feeders. They also supply unbalanced loads. Based on the model, the optimal size, locations and switching intervals of fixed and switched capacitors are determined. The objective is to maximize the net revenue savings resulting from power and energy reductions.

The paper, however, did not discuss optimal number of fixed and/or switched capacitors to achieve the maximum savings. Capacitor sizes are treated as continuous variables which is not the case in real-life where capacitor sizes are discrete. A numerical example is presented for a real multi-grounded, three-phase feeder with lateral branches and five wire sizes.

S. Ertem and J. Tudor presented an objective function representing monetary savings that result from capacitor allocation in terms of system voltages and angles and the reactive power to be allocated [4]. The constraints are the maximum and minimum system voltages. The method takes the load uncertainty into account. This is done to prevent both over-compensation and the under-compensation.

To reduce system variables and to avoid the numerical instability, sensitivity analysis and pattern recognition techniques are used. The proposed solution is based on non-linear programming technique where two models are presented. The first one solves the problem subject to approximate constraints. The output of this model is used as a starting solution to the second model. The second model has the exact formulation of the constraints using the method of approximate programming (MAP).

R. Rinker and D. Rembert presented a method to optimally allocate capacitors along a distribution line using the data gathered by reactive current recorders installed at major feeder taps [5]. This data is adjusted by a computer program for seasonal variation to represent an average week. The data is used later to achieve maximum savings by placing the proper sizes of capacitors at the appropriate places.

The method assumes that the current readings recorded at a node are applicable to the entire section which follows the node. It places the capacitors in different types and sizes in a systematic trial and error procedure. This method can be improved if a better way to account for seasonal changes is found. Currently, this is done by adjusting the data for the average week. It can also be improved if the program is extended to handle split feeders or nodes placed on significant branches.

M. Baran and F. Wu presented a nonlinear mixed integer programming formulation to solve the capacitor placement problem [6]. The objective function to be maximized is the revenue savings resulting from energy loss reduction minus the capacitors installation costs. Voltage constraints and load variations are considered as the problem constraints. The solution methodology decomposes the problem into a master and a slave sub-problems. In the master sub-problem, an integer programming is used to find the optimal location and the number of capacitor banks to be placed. The slave sub-problem is used by the master sub-problem to find the capacitor type and settings. The proposed solution model was tested by considering two different test systems. Although voltage regulators were not considered in this paper, the method can be extended to account for their presence.

Y. Baghzoz presented an exhaustive search method to solve for the optimal solution of the capacitor placement problem and nonlinear load models are incorporated in the problem formulation [7]. The paper assumes that the system is balanced and that all loads vary in a conforming way. The active and reactive powers represent the fundamental-frequency quantities. The loads are partitioned into linear and non-linear loads. The non-linear loads are assumed to have the same displacement factor.

To show the effect of the load model on the final solution, the problem considers three different load models. These are the base case model, the most accurate model and the constant impedance model. The problem constraints are the maximum number of capacitors assigned at a particular location. They also include the maximum number of capacitors on the entire feeder. The maximum and minimum r.m.s. voltage at a certain bus, the maximum peak value and the total harmonic distortion are also considered.

Numerical results show that consideration of load non-linearity substantially changes the optimal solution of the problem. The test system used by the author in this paper is a small one with 9 buses only. Exhaustive search, however, shows that it is not possible to be used for large systems.

S. Tripathy and M. Haridas discussed an analytical method for the problem of installing shunt capacitors on distribution feeders [8]. The paper gives a detailed derivation for the loss reduction in a distribution feeder. Based on this, the optimal size and locations of shunt capacitors are calculated. The paper also discusses the use of the normalization technique in case of different conductor sizes and non-uniformly distributed reactive loads.

C. Chen et al presented a computer simulation program to solve the optimal capacitor placement problem by means of non-linear programming while considering the mutual coupling among phase conductors [9]. Mutual coupling is determined by the types of conductors, horizontal and vertical distance among conductors.

The objective function to be minimized consists of peak power losses, energy losses and capacitor installation cost. It is assumed that the installation cost/kVar is constant. Also, the capacitor values are treated as discrete variables. The minimum and maximum bus voltages are taken as the system constraints. A 34-bus unbalanced and a 10-bus balanced test systems were considered. Simulation results revealed that the inclusion of mutual coupling is very important. If ignored, serious overcompensation and extra power losses may result. In addition, the effect of mutual coupling is more important for unbalanced systems.

Bala et al presented a sensitivity-based optimization method to optimally allocate shunt capacitors among a radial distribution feeder [10]. The solution should find optimal size, type and location of the capacitors. In most of the previous work, the feeder loading was assumed to be uniform at constant power factor. In this work, a distribution analyzer recorder (DAR) has been developed to collect data from the feeder. The data is collected over a period of several weeks.

The objective function is to minimize the peak power losses and the energy losses while considering the system released capacity and the installation cost of capacitors. The constraints are the system maximum and minimum bus voltages and the maximum number of capacitors to be installed on each location and on the entire feeder.

Several researchers attempted to solve the capacitor placement problem by using different heuristic and iterative methods. These methods provide reasonable solutions with minimum complexity.

Chiang et al solved the general capacitor placement problem in a distribution system by means of the simulated annealing method [11,12]. The objective of this work is to maximize the energy loss reductions in the system while considering the capacitors installation costs. The capacitor cost function is step-like and non-differentiable. The constraints are the upper and lower voltage limits and the load variations.

Chiang et al presented a more comprehensive methodology based on simulated annealing mixed with greedy search to solve the general capacitor placement problem [13,14]. The purpose of this mix is to get a good-quality solution in a shorter time. The proposed method can be applied to large scale unbalanced, radial or loop distribution network. Accurate mathematical modeling of distribution lines, shunt capacitors, transformers, loads and cogenerators were employed. The aim is to find the optimal location to install (or replace or remove) capacitors, types and sizes during each load level and the control schemes for each capacitor.

The objective function takes into consideration the installation (or replacement or removal) cost of capacitors and the system energy losses. The constraints of the problem are load flow, line flow capacity and voltage magnitude constraints. The cost function of capacitors is a step-like and hence a non-differentiable function. Capacitor sizes and control settings are treated as discrete variables.

Sundhararajan and Pahwa solved the general capacitor placement problem in a distribution system using a genetic algorithm [15]. Genetic Algorithm, as an optimization technique, can reach a near-optimal solution in a lesser time than that of the simulated annealing. The objective function presented is not constrained. However, if a constraint is to be incorporated, then a penalty function should be included. Sensitivity analysis is used in this paper as an aid for the Genetic Algorithm to help select the candidate locations of capacitors. Top two or three buses in each lateral branch are chosen as candidate locations. A 9-bus and a 30-bus test systems were used to check the robustness of the method.

Yann-Chang Huang et al introduced a Tabu Search-based method to solve the capacitor placement problem [16]. To start with, heuristic and engineering judgments are used to select the potential locations where capacitors can be installed. Then, a sensitivity analysis is used to determine the candidate locations. In comparison with simulated annealing, the authors concluded that Tabu Search method gives the same results with shorter computing time.

Z. Wu proposed to solve the capacitor placement problem by means of Maximum Sensitivity Selection (MSS) method [17]. The MSS decomposes the problem into sub-problems to make the solution simpler. The objective function considers the peak power loss, energy losses and the installation cost of capacitors. The problem constraints are system minimum and maximum voltages and total harmonic distortion. The paper assumes that all loads change in a conforming way, load variations can be approximated by discrete levels, loads are linear and balanced, skin effect of higher harmonics is neglected and the substation is the only harmonic source.

Karen Nan Miu et al proposed to solve the general capacitor placement problem by a Genetic Algorithm followed by a sensitivity-based heuristic method [18]. Genetic algorithm is employed to find a high quality solution that is used as an initial guess for the sensitivity-based heuristic. The objective function includes the cost of placement or replacement of capacitor banks and the cost of real power loss. The problem constraints are the power flow constraints, operational constraints on bus voltages and the line flow ratings. Simulation results revealed that the proposed hybrid algorithm outperformed the Genetic Algorithm alone and the sensitivity heuristic alone in terms of both speed and quality.

M. Baran and F. Wu solved the optimal sizing problem of capacitors placed on a radial distribution system as a special case of the general capacitor placement problem [19]. The sizing problem is formulated as a nonlinear programming problem. The formulation incorporates the ac power flow model for the system and the voltage constraints.

Y. Baghzouz and S. Ertem solved the optimal sizing of distribution capacitors as a special case of the general capacitor placement problem using a simple heuristic method based on the method of local variations [20]. Potential harmonic iterations like resonance conditions, high harmonic distortion factor and additional harmonic power losses are considered in the problem formulation. The savings associated with power loss reduction may have to be sacrificed to control the total harmonic distortion to acceptable limits. The paper assumes that the line capacitance are negligible, system is balanced, all loads are linear and time invariant, harmonic generation is only from the substation voltage supply, only fixed capacitors are used and capacitors are represented as constant admittances.

J. Grainger et al presented a generalized procedure based on non-linear programming for optimizing the net savings resulting from power loss reduction caused by capacitor installation [21]. The system unbalance is taken into account and mutual coupling between the phases is considered. The paper, however, assumes only fixed capacitors are to be installed. Moreover, capacitor sizes are treated as continuous variables. Also, capacitor installation cost is neglected.

Jin-Chang et al decouple the general capacitor placement problem into two sub-problems; the capacitor placement sub-problem and the real-time control sub-problem [22,23]. A quadratic integer programming based approach is proposed for the capacitor placement sub-problem to determine the number, locations and sizes of capacitors to be placed. The real-time control sub-problem is formulated as another quadratic integer programming problem to determine the control settings for the different loading conditions.

The distribution system under study is unbalanced with nonlinear loads. Load variation is taken into consideration by assuming different discrete load levels with different durations. The total energy loss is calculated by summing all the energy losses associated with each load level during its specified time period. Capacitor sizes are treated as discrete variables.

The objective function in this formulation is the cost of capacitors and the savings of energy loss reduction. There are two types of constraints associated the problem formulation of this paper, namely physical constraints, related to the upper and lower limits on the capacitor current magnitudes, and operational constraints related to the voltage magnitude and current flow capacity. A real 292-bus and a 394-bus test systems were used to check the feasibility and capability of the proposed method.

2.2 Scope of the work

The work of this thesis intends to solve the general CPP in distribution systems using various modern heuristic techniques, namely simulated annealing, genetic algorithm, tabu search and a hybrid algorithm formed by combining both simulated annealing and genetic algorithm.

The objective is to minimize the energy losses in the system while taking the capacitor installation costs into consideration. The capacitor cost is a step-like and, therefore, a non-differentiable function. Load variations, load constraints, operational constraints and constraints on capacitor types and sizes will be all considered in the problem formulation. Models of the distribution system at the fundamental frequency and at harmonic frequencies are established in order to include the non-linear loads into the problem formulation.

Nonlinear loads are included to make sure that the resulting harmonic distortion levels are within the acceptable limits.

The solution algorithms have been implemented into a software package in FORTRAN-77 and tested on a 69-bus radial distribution system and a 30-bus distribution system containing a loop.

Chapter 3

System Modeling & Problem Formulation

This chapter presents a mathematical formulation of the general capacitor placement problem. Practical constraints are taken into consideration. A sensitivity analysis used to select a candidate set of locations to install the capacitors is also presented.

3.1 Problem statement

The general capacitor placement problem can be formulated as a constrained optimization problem [18];

$$\min f\ (x,u) \tag{3.1}$$

subject to

$$F(x,u) = 0 \tag{3.2}$$

$$G(x,u) \leq 0 \tag{3.3}$$

where $f(x,u)$ is the objective function. The state variable x represents the state of the distribution system and the capacitor placement scheme is represented by the variable u. $F(x,u)$ represents the set of equality constraints and $G(x,u)$ represents the set of inequality constraints of the problem.

3.1.1 Assumptions

The following assumptions were considered while formulating the problem:

1. The system is balanced.
2. All the loads vary in a conforming manner.
3. The forecasted active and reactive powers provided by the load duration curve represent fundamental-frequency powers. Additional powers at harmonic frequencies are negligible.
4. Loads at bus "j" are partitioned into (w_j) nonlinear loads and $(1-w_j)$ linear loads.
5. Both clusters of linear and nonlinear loads at bus "j" have the same displacement factor, i.e. power factor at fundamental frequency.
6. Loads are represented as power sink.
7. Lines are modeled as a resistance in series with a reactance $(r + jx)$.
8. Skin and proximity effects are ignored at harmonic frequencies.

3.1.2 Load variations

To calculate the energy losses in the system, the load variations in the system for a given period of time T are taken into account. It is assumed that load variations could be approximated in discrete levels. In addition, all the loads are assumed to vary in a conforming way.

In consideration of these assumptions, the load duration curve is approximated by a piecewise linear function and the time period T is divided into intervals during which the load level is assumed constant as illustrated in Figure (3.1). We consider that there are three different load levels classified as peak, medium and light load level [11,16].

3.1.3 Capacitor size and control settings

Only the smallest standard size of capacitors and multiples of this standard size are allowed to be placed at the buses to have a more realistic optimal solution that can be implemented later with no difficulties. Capacitor banks are usually supplied in sizes ranging from 300 to 1800 kVar. In general, capacitors installed on feeders are equipped with necessary group fusing.

The fusing applications restrict the size of the bank which can be used. At 15 kV, the maximum sizes used are about 1800 kVar. Electric utilities do not usually install more than four capacitor banks on each feeder [24]. This criterion is adopted in the problem formulation.

In practice, both fixed and switchable capacitors are used. A fixed capacitor has the same kVar value at all the levels. If only fixed typc capacitors are utilized, the utility will experience a voltage rise and an excessive leading power factor at the feeder when it is lightly loaded. To avoid this, switched capacitors are used so that they can be switched to

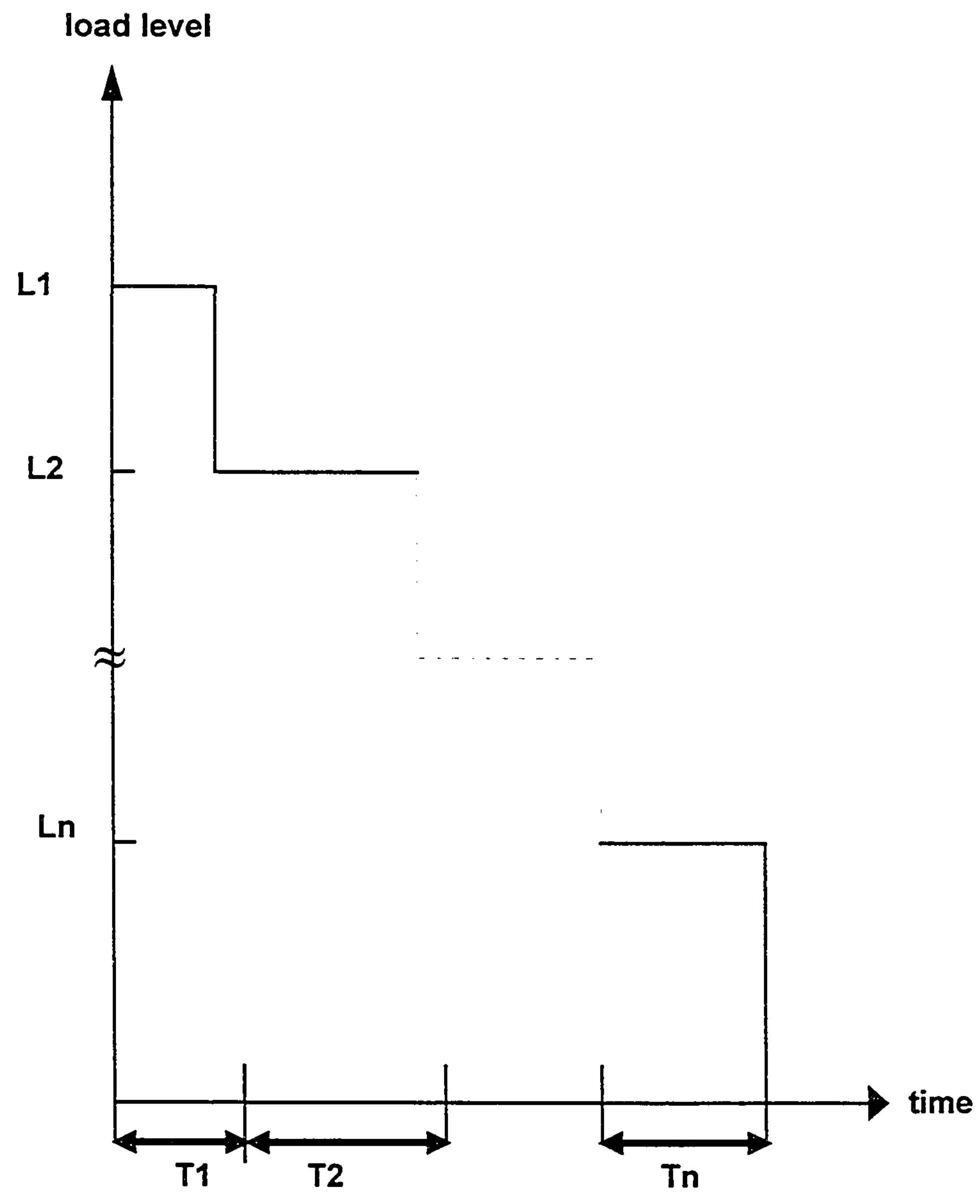


Figure 3.1: Load Duration Curve

suit the load conditions [8,24]. The maximum kVar value to which a switchable capacitor can be switched is at the peak load level.

Both fixed and switched capacitors are considered in the problem formulation. The capacitor sizes and control settings are treated as discrete variables and this makes the formulated problem a combinatorial one [16].

3.1.4 Objective function

The objective of the capacitor placement problem is to reduce the total energy losses of the system during all load levels while striving to minimize the cost of capacitors to be installed in the system [11,15,16]. With this, the formulated objective function consists of two terms. The first is the cost of capacitor placement and the second is the cost of the total energy losses.

The cost associated with capacitor placement is composed of a fixed installation cost and a purchase cost as illustrated in Figure (3.2). The cost function described in this way is a step-like function rather than a continuously differentiable function since capacitors, in practice, are grouped in banks of standard discrete capacities.

It should be pointed that since the objective function is non-differentiable, all nonlinear optimization techniques become awkward to apply. The usual practice in nonlinear programming optimization methods is to approximate the non-differentiable function with a differentiable one.

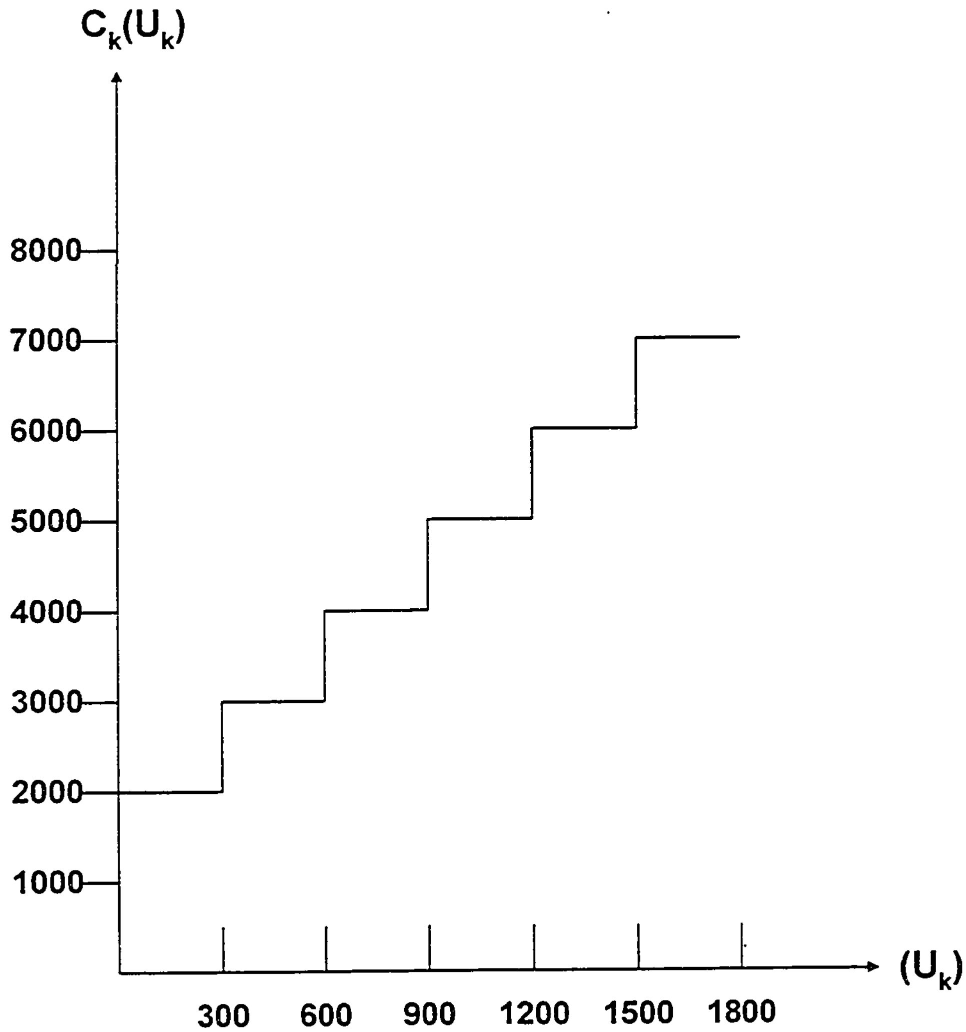


Figure 3.2: The Capacitor Investment Cost Function

The second term in the objective function represents the total cost of energy losses. This term is obtained by summing up the real power losses for each load level multiplied by the corresponding duration.

3.1.5 Load constraints

The substation must be able to provide the load demands and conductor losses of the feeders. This requirement is imposed by the power flow equations on the real power and reactive power injections at each node [10]. A Gauss-Seidel iterative method is used to solve the load-flow and either radial or loop systems may be studied.

3.1.6 Operational constraints

Voltages along the feeder are required to remain within upper and lower limits prior to, or after, the addition of capacitors on the feeder. Voltage constraints can be taken into account by specifying the upper and lower bounds of the magnitude of the node r.m.s voltages [10,17].

3.1.7 Modeling at fundamental frequency

Since nonlinear loads are included in the problem formulation, system modeling at fundamental frequency and harmonic frequencies shall be established. At the fundamental frequency, loads are modeled as constant sink of active and reactive powers. The voltages obtained from the Gauss-Seidel iterative method at all the buses during different load levels are considered to be the fundamental voltage values. Fundamental currents injected at the i-th bus during the k-th load level are calculated using the following equation.

$$I^1_{ik} = \frac{(P_{ik} - jQ_{ik})}{(V^1_{ik})^*} \tag{3.4}$$

where

P_{ik} Active power at the i-th bus during the k-th load level

Q_{ik} Reactive power at the i-th bus during the k-th load level

V^1_{ik} Fundamental voltage at the i-th bus during the k-th load level

3.1.8 Modeling at harmonic frequencies

At harmonic frequencies, shunt capacitor is represented by the following admittances at the n-th harmonic frequency.

$$y^n_c = n\, y^1_c \tag{3.5}$$

where

y_c^1 Shunt capacitor admittance at fundamental frequency

y_c^n Shunt capacitor admittance at n-th harmonic frequency

n Harmonic order of interest

The admittance of the line between buses 'i' and 'i+1' at n-th harmonic frequency is given by the following equation:

$$y^n_{i,i+1} = \frac{1}{R_{i,i+1} + jnX_{i,i+1}} \tag{3.6}$$

where

$R_{i,i+1}$ Resistance of the line between buses 'i' and 'i+1'

$X_{i,i+1}$ Reactance of the line between buses 'i' and 'i+1'

Substation transformer is represented by its short circuit admittance y_t^n scaled to the harmonic order of interest.

With respect to the linear loads, it is suggested to use a generalized model which is composed of a resistance in parallel with an inductance selected to account for the respective active and reactive powers at fundamental frequency. Load admittance at the k-th load level is expressed as

$$y_{ik}^{\ln} = \frac{1-w_i}{\left|V_{ik}^1\right|^2}(P_{ik} - j\frac{Q_{ik}}{n}) \tag{3.7}$$

where

w_i Percentage of the nonlinear loads at bus 'i'.

Nonlinear loads are represented by simple ideal current sources. The overall voltage at the i-th bus during the k-th level can be evaluated by the following expression.

$$\left|V_{ik}\right| = \sqrt{\sum_{n=1}^{N}\left|V_{ik}^n\right|^2} \tag{3.8}$$

where

V^n_{ik} n-th harmonic voltage at bus 'i' during the k-th load level

N Maximum harmonic order considered

The maximum total harmonic order at the i-th bus during the k-th load level is given by the following equation.

$$THD_{ik}(\%) = \frac{100}{\left|V_{ik}^1\right|}\sqrt{\sum_{n\neq 1}^{N}\left|V_{ik}^n\right|^2} \tag{3.9}$$

The distortion factor constraints of voltage can be taken into account by specifying the maximum distortion factor of the voltage [17].

3.2 Mathematical formulation

With all of the above considerations, this section presents a mathematical formulation for the CPP. First, we define the symbols used in this model as shown hereunder.

i : Load level

k : Location (bus)

x^i : A vector of state variables

u^i : A vector of control variables (capacitor placement scheme)

n_c : Possible Locations to install capacitors

u_k^o : Size of capacitor installed at location k

u_k^i : Size of capacitor installed at location k during load level i

k_e : Energy cost per unit

n_t : Number of load levels

T_i : Duration of load level i

u_s : Standard capacitor size of one bank

N_C : Set of possible locations to install capacitors

N_T : Set of different load levels

$|V_{ik}|$: Total rms voltage at the k-th bus during the i-th load level

$V_{\min}$: Minimum allowable operating voltage

$V_{\max}$: Maximum allowable operating voltage

C_1 : Set of fixed capacitors

C_2 : Set of switched capacitors

THD_{ik} : Total harmonic distortion at the k-th bus during the i-th load level

$THD_{\max}$: Maximum allowable total harmonic distortion.

$(l_k)_{\max}$: Maximum number of capacitor banks to be installed at location (bus) k

With these symbols, the model is shown as follows:

$$\text{minimize} \sum_{k=1}^{n_c} C_k(u_k^o) + k_c \sum_{i=1}^{n_t} T_i P_{loss,i}(x^i, u^i) \tag{3.10}$$

subject to

1. $u_k^o = l_k * u_s$ where l_k is a non-negative integer, $k \in N_C$

2. u_k^i = discrete variable, $i \in N_T, k \in N_C$

3. Power flow constraints $P_{flow}(x^i, u^i) = 0 \quad i \in N_T$

4. Operational constraints $V_{\min} \le |V_{ik}| \le V_{\max}$

5. For $k \in C_1$ = fixed cap $u_k^i = u_k^j \le u_k^o$ for $i, j \in N_T$

6. For $k \in C_2$ = Switched cap. $0 \le u_k^i \le u_k^o$ for $i \in N_T$

7. $THD_{ik} \le THD_{\max}$

8. $l_k \leq (l_k)_{\max}$

where

$\sum_{k=1}^{n_c} C_k(u_k^o)$ represents the installation cost of capacitors

$k_e \sum_{i=1}^{n_t} T_i P_{loss,i}(x^i, u^i)$ represents the cost of the total energy losses

3.3 Sensitivity analysis

Sensitivity analysis is a systematic procedure to select those locations having maximum impact on the system real power losses with respect to the nodal reactive power. Locations of high sensitivities are selected as the candidate locations for placing the capacitors in the distribution system. Sensitivity Analysis basically helps in reducing the search space for the optimization procedure [15,25].

We consider Sensitivity Analysis together with heuristics and engineering judgement to determine the candidate locations.

Complex power losses are given as in [15,18,25].

$$P_L + jQ_L = VI^* = VY^*V^* \tag{3.11}$$

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_i - \theta_j - \delta_{ij}) \tag{3.12}$$

Sensitivity of system's real power losses with respect to the nodal reactive power

$$\frac{\partial P_L}{\partial Q} = \left(\frac{\partial P_L}{\partial V}\right)\left(\frac{\partial V}{\partial Q}\right) \tag{3.13}$$

$$\frac{\partial P_L}{\partial V_i} = 2\sum_{j=1}^{N} V_j Y_{ij} \cos\delta_{ij} \cos(\theta_i - \theta_j) \tag{3.14}$$

$$\frac{\partial P_L}{\partial \theta_i} = -2V_i \sum_{j=1}^{N} V_j Y_{ij} \cos\delta_{ij} \sin(\theta_i - \theta_j) \tag{3.15}$$

In order to determine the sensitivity of a bus, solve for $\frac{\partial P_L}{\partial Q}$ in the following equation:

$$\begin{bmatrix} \frac{\partial P_L}{\partial \theta} \\ \frac{\partial P_L}{\partial V} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} \\ \frac{\partial P}{\partial V} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \frac{\partial P_L}{\partial P} \\ \frac{\partial P_L}{\partial Q} \end{bmatrix} \tag{3.16}$$

$\frac{\partial P_L}{\partial Q}$ is a (n x 1) column matrix, where n is the number of buses. The sensitivity factor (SF) of a certain bus is determined by its respective element of the $\frac{\partial P_L}{\partial Q}$ matrix. The buses are ordered according to their sensitivity values as calculated above. Buses of high sensitivity factors have more chances of being selected as candidate locations for capacitor installation.

In addition to the value of the sensitivity factor of a certain bus, the size of the load connected to the bus affects the selection process of the bus as a candidate location for capacitor installation. Buses with big loads have more chances of being selected. The candidate set of buses is chosen to cover different areas (branches/laterals) of the distribution system under study rather than being concentrated at a particular area.

Chapter 4

Solution Methods

In this chapter, different heuristic optimization methods are discussed. Application of simulated annealing (SA), genetic algorithm (GA) and tabu search (TS) to solve the capacitor placement problem is presented. Design of a successful solution algorithm using these heuristic optimization tools is dependent on the way their parameters are selected. Therefore, some hints that help select the parameters properly are highlighted. Finally, the idea of combining two or more of these heuristic methods to form a hybrid algorithm is addressed.

4.1 Simulated annealing (SA)

This section introduces simulated annealing (SA) as a heuristic optimization method. It also describes the basic outline of the method. Features and disadvantages of SA are listed. In addition, the section explains how a SA-based algorithm is designed successfully. Moreover, it discusses the application of SA to solve the CPP in distribution systems.

4.1.1 Introduction

In physical systems, the process of cooling a material in a heat bath is known as annealing. The ideas which form the basis of simulated annealing were first published by Metropolis et al. in 1953 in an algorithm to simulate the annealing process. The structural properties of a solid material, if heated past its melting point and then cooled back into a solid state, depend on the cooling rate of the liquefied material [26]. While slow cooling produces a large defect-free crystal, rapid cooling yields a defective crystal with a number of imperfections [4,26].

The annealing process can be simulated by regarding the material as a system of particles. Essentially, Metropolis's algorithm simulates the change in energy of the system when subjected to a cooling process, until it converges to a steady 'frozen' state. In the early 1980s, Kirkpatrick et al. suggested that this type of simulation could be used to find the optimal solution of an optimization problem by mapping the elements of the physical cooling process onto the elements of an optimization problem as shown in table (4.1) [26].

Simulated annealing can be regarded as a variant of local or neighborhood search. In local search, a subset of feasible solutions is explored by repeatedly moving from the current solution to a neighboring one. For a minimization problem, local search always moves in a direction of improvement by employing a descent strategy. Such a strategy, however, results in a convergence to a local rather than a global optimum. To overcome this problem, a number of approaches have been suggested. It may be possible to widen

Table 4.1:Mapping of the Elements of a Physical System and the Elements of a Combinatorial Optimization Problem

Thermodynamic simulation	**Combinatorial optimization**
System states	Feasible solutions
Energy	Cost
Change of state	Neighboring solution
Temperature	Control parameter
Frozen state	Heuristic solution

the scope of the search by increasing the neighborhood complexity. In addition, the search may be started from different points since the optimal solutions obtained by these descent strategies are totally dependent on the starting solution(s) employed, as illustrated in Figure (4.1). In fact, none of these solutions have proven to be entirely satisfactory.

A reliable heuristic shall be less dependent on the starting point. It is clear from Figure (4.1) that this shall involve some uphill moves in a controlled manner. In simulated annealing, uphill moves are allowed according to certain criteria that takes the state of the search process into consideration [13]. Frequency of uphill moves is governed by a probability function that changes as the algorithm progresses [26].

Because of its simplicity, generality, solid mathematical foundation and ability to produce promising results, the widespread use of simulated annealing has increased [13].

4.1.2 Basic outline of simulated annealing

Suppose we have an objective function to be minimized subject to a set of constraints. Let's assume that 'S' is a set of feasible solutions and f: $S \rightarrow R$ is a cost function that can be calculated for all $s \in S$ and selecting the minimum. In most real-life problems, however, this is impractical due to the large size of 'S'.

Simulated annealing, as a variant of local or neighborhood search, searches only a small subset of the solution space by defining a neighborhood structure on it and searching the neighborhood of the current solution for an improvement. Neighborhood is sampled randomly.

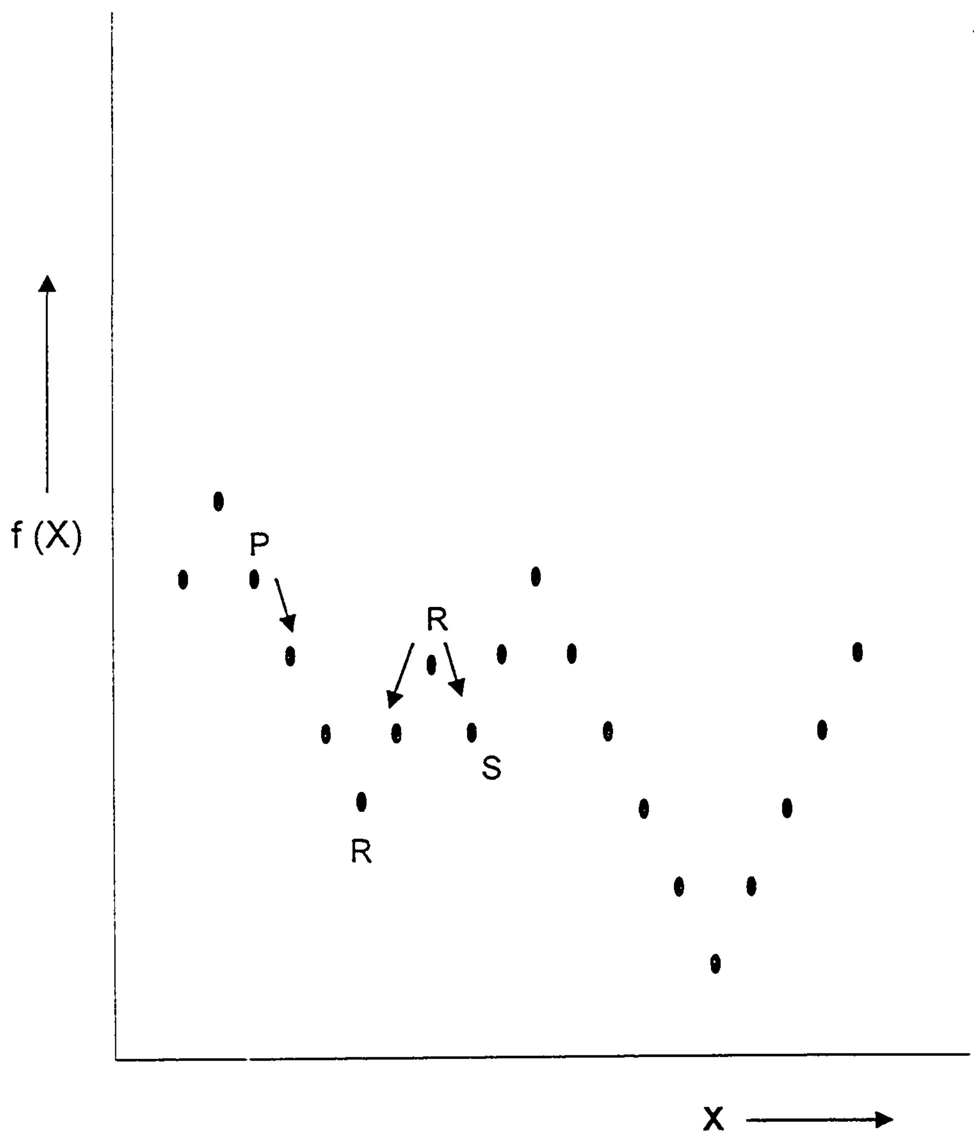


Figure 4.1: Illustration of a Descent Strategy

Simulated annealing algorithm starts by selecting an initial solution s_o at random. The initial solution is regarded as the current solution. The annealing process consists first of melting the system being optimized at some initial temperature t_o which is usually high. In SA, the concept of the temperature of a physical system has no obvious equivalent in the systems being optimized [27]. Then the temperature is lowered gradually by means of a temperature reduction function α, similar to decreasing an objective function value by a series of improving moves [27,28].

A neighbor to the current solution is selected at random and its corresponding cost function is calculated. If the calculated cost function is less than that associated with the current solution, then the move is accepted and the current solution is replaced by this neighbor. The neighbor is regarded as the current solution. On the other hand, if the calculated cost function is greater than that of the current solution, then the move is accepted probabilistically. A random number X is generated in the range (0,1) and a probability function $p(\delta)$ is determined as shown below:

$$p(\delta) = e^{-\delta/t} \quad (4.1)$$

where

$$\delta = f(s) - f(s_o) \quad (4.2)$$

$$t = \text{temperature}$$

The move to the new state (solution) is accepted if $X < p(\delta)$. If this is not the case, however, then the move is rejected.

Probabilistic acceptance of the moves in SA represents the uphill moves which are necessary to avoid convergence to local optimal solutions as discussed earlier. Control of uphill moves is achieved as the probability function is dependent both on the difference in the calculated cost functions and the temperature of the state of the search process.

At each temperature, a predefined number of moves is performed before the temperature is lowered or cooled by the reduction function (α). The algorithm is repeated until the stopping condition is satisfied. Figure (4.2) illustrates the basic outline of SA algorithm.

4.1.3 Features and disadvantages of simulated annealing

Simulated annealing, as outlined previously, has the following attractive properties:

1. It can handle various types of constraints such as equality, inequality, differentiable and non-differentiable constraints [13].
2. It starts with any initial solution and converges to a near-global optimal solution [13].
3. It is simple to implement and widely applicable for combinatorial optimization problems [26].
4. It yields a global optimal solution with a probability equal to 1 after a sufficient number of iterations at each level with a suitable perturbation scheme and a sufficiently slow cooling schedule [11,13,28].

On the other hand, simulated annealing has the following shortcomings.

1. It takes considerable amount of computation efforts to converge [13].
2. Simulated annealing best parameters are obtained by trail and error process until good results are achieved. This is a time consuming task when solving difficult problems.

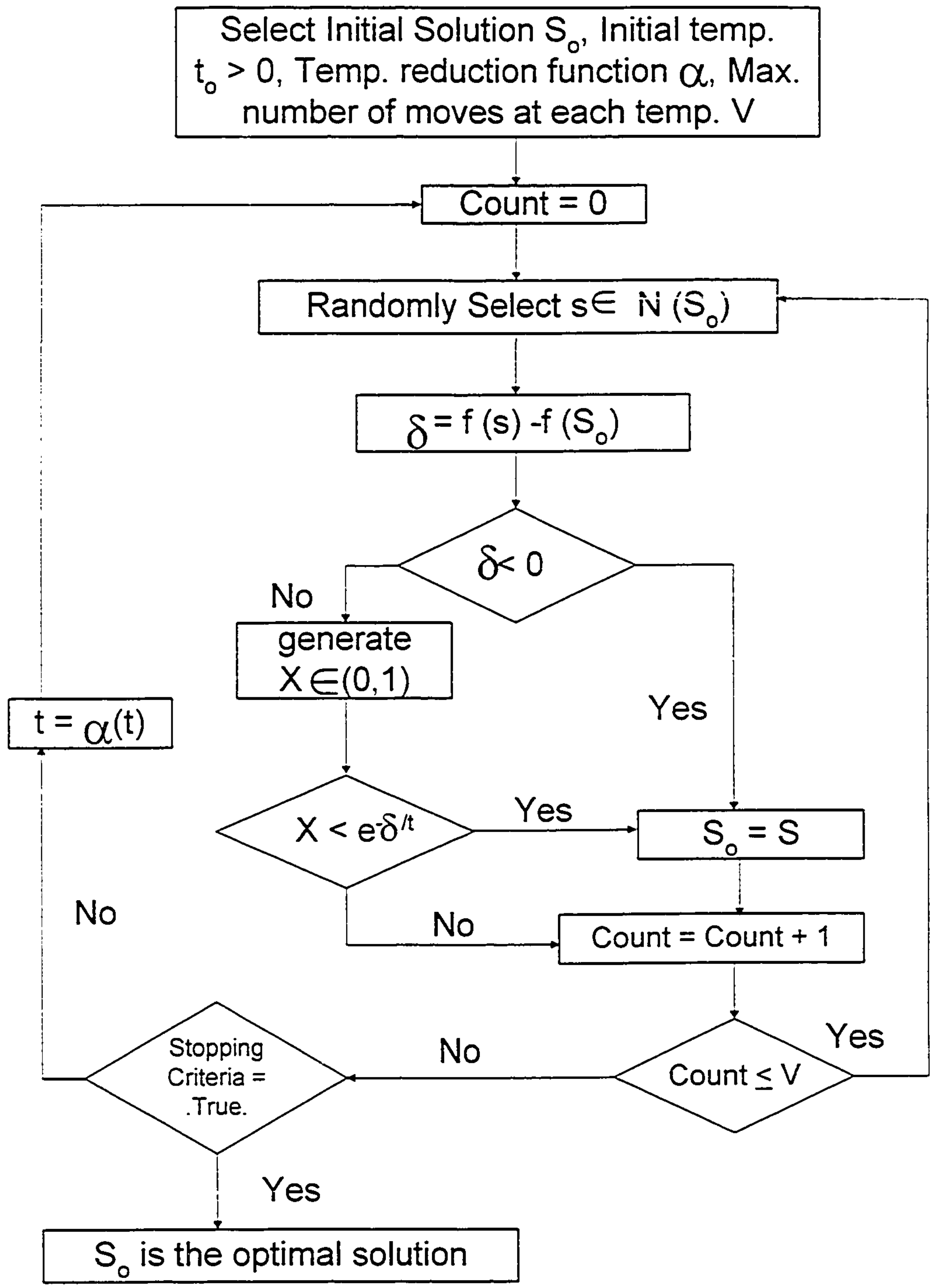


Figure 4.2: Simulated Annealing Algorithm

4.1.4 Design of a successful SA algorithm

There are four important elements in the design of an annealing-based algorithm. These are the configuration space, the set of feasible moves, the cost function and the cooling schedule [11,27].

The configuration space is defined as the set of allowed system configurations over which the optimal system configuration is to be searched for [12].

A set of feasible moves is required in the design of a SA-based algorithm to perturb a current system configuration in order to get a new system configuration [12]. This is usually achieved by adding an element to or subtracting an element from the set of solution variables. It may also be achieved by swapping the values of two randomly selected solution variables [26]. The number of moves allowed at each iteration (temperature) is very significant in the design of SA algorithm.

The cost function provides a qualitative measure of the fitness of a newly generated solution. In minimization problems, for example, the lower the value of the cost function associated with a particular solution, the more suitable the solution is.

The fourth element in the design of a SA algorithm is the cooling schedule. The cooling schedule consists of two components, namely the initial temperature and the temperature-lowering scheme.

In addition to the above elements, the designer of a SA algorithm has to decide when to stop or terminate the algorithm. This is known as the stopping criterion of the algorithm.

Simulated annealing framework is conceptually straightforward. However, design of successful annealing-based methodology requires considerable engineering judgement [11]. Several decisions must be made prior to implementing SA for a particular problem. These decisions are classified into two categories as listed below:

1. **Generic Decisions**: These are concerned with the parameters of the annealing algorithm itself like the initial temperature, temperature lowering scheme and the stopping criterion.
2. **Problem-specific Decisions**: These are related to the problem to be solved such as the choice of solution space, cost function and neighborhood structure.

Improper make of generic and problem-specific decisions affects both the efficiency and the solution quality of the algorithm. As it affects both the efficiency and the solution quality obtained by the annealing-based solution algorithm, the configuration space must be properly designed. The configuration space domain may be reduced without eliminating the portion of the configuration space which contains the optimal configuration. Such reduction can enhance the efficiency of the algorithm without compromising the final solution quality. However, this requires good engineering judgement [12].

SA-based algorithm designer shall decide whether to consider the exact objective function itself as the cost function or to use a function that does not accurately represent the true objective as a cost function. Sometimes, SA algorithm may be formulated to accept both feasible and infeasible solutions. In such a case, however, constraint(s) violation associated with infeasible solutions shall be accounted for. This is usually achieved by including a penalty factor in the objective function. Different infeasible solutions have different degrees of infeasibility. In other words, the extent to which the problem constraints are violated differs from one solution to another. Selection of penalty factors that takes this into consideration is, again, another decision to be made by the designer.

The third problem-specific decision to be made by the SA algorithm designer is related to the neighborhood structure. One important consideration in determining the neighborhood structure is to ensure that every solution is reachable from every other solutions. A variety of moves or perturbation mechanisms shall be employed to make sure that neighboring solutions of a particular current solution are adequately covered. This, in turn, will help reduce the probability of premature convergence to a local optimal solution. A proper decision concerning the maximum number of moves to be executed at every iteration (temperature) is to be made. Designer shall decide to have either a fixed number of moves at every iteration or a variable number that changes as the algorithm progresses. Most of the useful work of a SA algorithm is done in the middle of the schedule. Because of this, some researchers propose to increase the number of moves during the middle of the search [26]. Number of allowed moves at each iteration is determined empirically by trial and error process since it depends on the solution space itself. In addition, it shall be properly tuned with other parameters of the algorithm for the success of the design.

In SA, rearrangements that cause large changes in the cost function take place at high temperatures, while the small changes are deferred until low temperatures [27]. Therefore, the initial temperature shall be set high enough such that the initial ratio between the number of accepted moves and the total number of moves performed (known as the acceptance ratio) is almost equal to 1 [12]. An almost free exchange of neighboring solutions at high initial temperature is required in order for the optimal solution to be independent of initial solution. As the number of constraints in the problem increases, the tendency to reject randomly generated solutions increases and hence the initial acceptance ratio shall be reduced accordingly. Proper initial temperature is determined after some experimentations.

The temperature-lowering scheme is very crucial as it controls the life span of a SA algorithm. If SA is too fast, one expects a pre-mature convergence of the algorithm. On the other hand, if SA is too slow, one must wait for a long period of time prior to obtaining a good approximation of the global optimum [29]. Slow annealing corresponds to more computation time required by SA and rapid annealing corresponds to less computation time. The designer may use a geometric reduction in the temperature where the temperature is multiplied by a constant number (α) ranging from 0.8 to 0.99. Moreover, he may use different values of (α) as the algorithm progresses. Also, he may use a reduction function such as the one suggested by Lundy & Mees in [26].

The stopping criterion is another parameter to be designed in the SA algorithm. The designer may stop the algorithm if a pre-specified number of iterations is completed. It may be possible to stop the algorithm if a pre-specified acceptance ratio is attained. Also, the algorithm may be terminated based on a mathematical formula like the one suggested by Lundy & Mees in [26]. The stopping criteria shall be tuned together with the other parameters like the initial temperature, number of allowed moves per iteration and the cooling schedule in order to get good-quality solutions.

Best parameters are not easy to be determined. Only after much experimentation, good parameters may be achieved. It is not possible to set down a series of rules that will always define the best choices of the parameters of an annealing algorithm used for a solution of a specific problem [26].

4.1.5 Application of SA to solve CPP in distribution systems

Simulated annealing, as a heuristic optimization method, is very useful when dealing with real-life problems which are characterized by a large number of constraints like the CPP in a distribution system. For this particular problem, generic and problem-specific decisions were made as highlighted hereunder:

1. The configuration space is reduced, in order to enhance the algorithm efficiency, by means of the sensitivity analysis carried out prior to SA application to solve CPP in distribution systems. Only a subset of the most sensitive buses is selected as a set of candidate locations to place fixed or switched capacitors instead of considering all the buses of the network. Moreover, capacitor control settings at the peak load are assumed to be always greater than or equal to the settings at the medium load. Similarly, capacitor control settings at the medium load are always assumed to be greater than or equal to the settings at the light load.
2. Five different types of moves are employed to perturb the current system configuration to get a new configuration. The first type of moves adds a positive integer multiple of a standard size of capacitor bank to a randomly selected bus. The addition operation in this move is replaced by a subtraction operation in the second

type of moves. The third type of moves exchanges the capacitor control settings of two randomly selected buses with each other. In the fourth type of moves, the control settings of a capacitor at a randomly selected bus during different load levels are changed synchronously. Instead, they are changed asynchronously in the last type of moves. In the design of a SA-based solution algorithm, these moves are executed according to pre-specified percentages assigned to each type.

3. The number of moves per iteration is designed as a fixed value throughout the search process.
4. The objective function, formulated earlier, is considered to be the cost function of the algorithm. Every generated solution is checked for its feasibility. If not feasible, the solution is rejected. Therefore, no penalty factors are added to the cost function to account for the infeasible solutions.
5. The initial temperature is set empirically if a pre-specified initial acceptance ratio is attained. As the number of constraints increases in the problem, the probability to reject randomly generated solutions increases as well. Due to this, the setting of the initial acceptance ratio is lowered as the number of constraints in the system increases.
6. The temperature-lowering scheme is designed using a constant number ranging between 0.8 to 0.99 throughout the search. This number is referred to as the cooling factor.
7. The stopping criterion of the algorithm is satisfied if no improvement is encountered in the optimal solution during the last pre-specified number of iterations.

The procedure of SA-based solution algorithm can be summarized by the following steps:

1. Input system and network data, integer seed, cost of capacitors and parameters of the annealing algorithm.
2. Calculate the system voltages, power losses during each load level and the total harmonic distortions for the case of nonlinear loads prior to capacitor placement.
3. Generate an initial feasible solution using a combination of the moves discussed earlier and calculate the associated cost function.
4. Perturb to obtain neighboring solutions by executing different types of moves based on their pre-specified percentages.
5. Check the feasibility of the new configuration. If not feasible go to 4, otherwise proceed to 6.
6. Design a proper cooling schedule. At each temperature, perform a number of moves. For any move do step (7) and step (8). Otherwise, proceed to step (9).
7. Generate a new feasible configuration.
8. Update the system configuration.
9. Check the stopping criterion. If not satisfied, go to (6); otherwise proceed to the next step.
10. Print out the optimal configuration.

4.2 Genetic algorithm

This section introduces genetic algorithm (GA) as a heuristic optimization method. It also describes the algorithm framework. Features and shortcomings of GA are listed. In addition, the section explains how a GA-based algorithm is designed successfully. Furthermore, it discusses the application of GA to solve the CPP in distribution systems.

4.2.1 Introduction

Genetic algorithms were initially developed by Holland and his associates in the 1960s and 1970s. Since their early development, genetic algorithms have been successfully applied to a wide variety of problems including combinatorial optimization problems. The name genetic algorithm originates from the analogy between the representation of a complex structure by means of a vector of components of the genetic structure of a chromosome. In selective breeding of plants and animals, for example, offspring which have certain desirable characteristics are sought. Offspring's characteristics are determined at the genetic level by the way the parents' chromosomes combine. In a similar way, we often intuitively combine pieces of existing solutions in seeking better solutions to complex problems. Although the parallel is not exact, it was sufficiently persuasive for Holland to propose the problem-solving methodology [26].

The idea of a genetic algorithm can be viewed as an intelligent exploitation of a probabilistic or random search which is based on the mechanics of natural selection and genetics [26,30,31]. The concepts of selective adoption and survival of the fittest are applied to search the parameter space to determine the optimal solution by way of randomized information exchange [15].

4.2.2 Genetic algorithm framework

There are four components in the design of a GA-based solution methodology. These include the initialization of the algorithm, fitness evaluation, selection and genetic operators [18].

Algorithm initialization is the process of randomly generating a set of initial feasible solutions forming the so-called "initial population". The number of these solutions is referred to as the "population size". Each iteration in a genetic algorithm, known as a "generation", results in a new set of feasible solutions [30].

As in the case of simulated annealing discussed previously, a genetic algorithm needs some fitness measure to determine the relative 'goodness' of a particular solution. This can be obtained either by direct evaluation of the objective function or by some other indirect means. Fitness evaluation is the criterion guiding the search process of a genetic algorithm.

In genetic algorithms, parents are selected to produce offspring. Selection process can be carried out in different ways. One way is to choose one parent on a fitness basis (the better the fitness value, the higher the chance of it being selected), while the other parent is selected randomly. Another way is to select both the parents at random [15,26].

Genetic operators are the probabilistic transition rules employed by a genetic algorithm. A new and improved population is generated from an old one by applying genetic operators [15]. Operators used by genetic algorithms include reproduction, crossover and mutation [30]. Reproduction is defined as a random pairing of trial solutions from a population to create one or more offspring [28]. Reproductive chances are assigned to each individual in the population during parent selection. Many methods are used to accomplish this task. Proportionate selection is one of these methods where probabilities of individuals being selected are calculated proportional to their fitness [31].

Crossover is the process of choosing a random position in the solution and swapping the characters around this position with another similarly partitioned solution [15,26]. The random position is referred to as "the crossover point". In other words, crossover defines the outcome as gene exchange [28]. Crossover operator proved very powerful in genetic algorithms. Mutation is the process of random modification of a particular value of a solution with a small probability [15]. Mutation is applied to alter some genes in the solutions [31]. When a gene exchange resulting from application of a crossover operator is not meeting appropriate restriction, mutation might be very helpful in providing a proper gene exchange amendment [28]. Mutation is generally seen as a background operator that provides a small amount of random search. It increases the population diversity. It also helps expand the search space by reintroducing information lost due to premature convergence. Therefore, it drives the search into unexplored regions [15,31].

In addition to the above components, the stopping criterion of the algorithm is of great significance. It determines when the algorithm shall be stopped or terminated and thus, considering the best solution obtained so far as the optimal solution.

4.2.3 Design of a successful GA-based solution methodology

In designing a GA-based solution methodology, several decisions concerning the algorithm parameters shall be properly made in order to obtain high-quality solutions. Pre-mature convergence to a local optimum may result if the algorithm parameters are not selected in an appropriate manner.

Population size and the way the initial population is selected will have a significant impact on the results [26]. Initial population could be seeded with heuristically chosen solutions or at random. In either case, the initial population should contain a wide variety of structures [15]. The population size and the initial population are selected such that the solution domain associated with the population is sufficiently covered. The population size depends on the criteria for selecting the initial solutions [31]. A constant size population of solutions shall be judged by the algorithm designer [18]. If the population size is too small, the solution domain will not be adequately searched and, thus, resulting in poor performance. Premature convergence to local solutions can be prevented by using a large population size. However, this may slow down the convergence rate [15,26].

The performance of a genetic algorithm is highly sensitive to the fitness values. The fitness value may be selected as the objective function to be optimized [15]. Some researchers, however, believe that the objective function value is a naive fitness measure. Therefore, using the objective function value associated with each solution as a fitness measure is rarely a good idea to some researchers [26]. When applying a crossover operator, the resulting offspring can be either feasible of infeasible. There are two ways to deal with infeasible solutions. One way is to design heuristic operators transforming infeasible solutions to feasible ones. The second is by penalizing this infeasibility in the objective function. In the latter case, selection of proper penalty factors is another decision to be made by the algorithm designer.

When applying a crossover operator, the algorithm designer shall choose among a single-point crossover or a multi-point crossover. Although a single-point crossover proved very powerful in a lot of GA applications, some researchers reported good performance of GA using a multi-point crossover [26,31].

Crossover rate and mutation rate play a very important role in the performance of genetic algorithm. A higher crossover rate introduces new solutions more quickly into the population. If the crossover rate is too high, high-performance solutions are eliminated faster than selection can produce improvements. A low crossover rate may cause stagnation due to the lower exploration rate [15]. Mutation rate shall not be too high in order not to prevent crossover from doing its work properly [26]. Some researchers reported that a variable mutation rate rather than a fixed one is more beneficial to be utilized. In the initial stage of the GA, it is recommended to start with a high crossover rate and a low mutation rate since the crossover is mainly responsible for the search at this stage. As the algorithm progresses, the crossover operator becomes less productive and therefore, the mutation rate shall be increased [26,31].

Simple GA involving just mutation and crossover has proved to be quite powerful enough. Some designers proposed to add an inversion operator where a section of a solution is 'cut out' and then re-inserted reversly. However, it has not been found significantly useful. It may be used instead of mutation operator to explore new regions of the searching domain [26].

As pointed out earlier, newly generated solutions replace existing solutions in subsequent generations of GA. Two replacement approaches are available to the algorithm designer to select among which. These are the incremental or 'steady-state' approach and the generational approach. In incremental or steady state replacement, once a new feasible solution has been generated, it will replace an above-average fitness value member chosen randomly. Members that fitness values are better than the calculated average are transferred to the next generation with no change. In generational replacement a new population of children is generated to replace the whole parent population [26,31]. The steady-state replacement approach has the following advantages [26,31].

1. If steady-state replacement approach is not employed, there will be no guarantee that the best solution in the current population will survive into the next generation. With this approach, best solutions are always kept in the population and the newly generated solution is immediately available for selection and reproduction.
2. It is more efficient when compared to the generational approach. Faster convergence is usually expected with this approach.
3. It prevents the occurrence of duplicates. Duplication is unhelpful since it wastes resources on evaluating the same fitness function and it distorts the selection process by giving extra chances to the duplicate solutions to reproduce.

Researchers, however, reported some success with the generational replacement approach. The genetic algorithm can be designed to stop if a pre-specified number of iterations is completed or if no improvement is encountered in the optimal solution during a given number of consecutive iterations. The stopping criterion shall be properly tuned with the other parameters like the population size, crossover rate and mutation rate in order to obtain a high quality solution.

4.2.4 Application of GA to the CPP in distribution systems

Because of its simplicity, generality and ability to cope with practical constraints, a genetic algorithm has been designed to solve the general CPP in a distribution system. The following remarks shed some light on the design aspects of the algorithm as applied to the CPP:

1. The algorithm is preceded by a sensitivity analysis which provides a subset of buses representing a set of candidate locations to install both fixed and switchable capacitors instead of dealing with all the buses in the network. The control settings of a switched capacitor installed at a particular bus during the peak load period are set higher than or equal to the settings during the medium load period. Similarly, capacitor control settings during the medium load period are greater than or equal to the settings during the light load period. This assumption together with the sensitivity analysis are deliberately incorporated in the design to reduce the searching domain and, hence, enhancing the algorithm efficiency.
2. The same set of moves discussed in the previous section of SA is employed by the GA to obtain an initial population containing a pre-specified number of feasible solutions.
3. The population size is a fixed value and the same is determined empirically by trial and error process.

4. The objective function itself is used to provide fitness values of the newly generated solutions. Once a new solution is generated, its associated feasibility is checked. Only if feasible, the solution is accepted. Otherwise, it is rejected. Therefore, no factors penalizing the infeasibility are included in the objective function.
5. Reproduction, crossover and mutation are applied as genetic operators in the algorithm design. No additional operators such as the inversion operator are considered in the design process.
6. A single-point rather than a multi-point crossover is selected in the design of the algorithm.
7. The algorithm is designed based on a fixed, rather than a variable, mutation rate throughout the search.
8. Mutation and crossover rates are determined empirically by trial and error process.
9. Steady-state replacement approach is selected in the design of the algorithm. In every generation, the average fitness value of all the solutions is calculated. Individuals (solutions) that fitness values are less than the calculated average fitness value are allowed to propagate to the subsequent generation with no change. The remaining solutions in the subsequent generation are formed by applying both crossover and mutation operators at pre-specified rates.
10. In selecting the parents to produce offspring, one parent is selected according to the following probability function [31]:

$$P_i = \frac{1/f_i}{\sum_{i=1}^{N} 1/f_i} \tag{4.3}$$

f_i : fitness of the i-th individual in the population

N : Population size

The better the fitness value of a solution, the greater the chance for it being selected as a parent. The other parent is selected randomly.

11. The algorithm is designed to stop if no improvement is achieved during a given number of consecutive iterations. The stopping criterion is tuned with the other algorithm parameters by trial and error process.

Based on the above remarks, a GA-based solution methodology applied to the CPP has been implemented. Figure (4.3) represents the algorithm flowchart. The algorithm procedure can be summarized as follows:

1. Read system and network data. Input the cost of capacitors (cc), minimum and maximum allowable operating voltages (V_{min} and V_{max}) respectively. Input algorithm parameters, i.e. population size (N), crossover rate (C_r) and mutation rate (m_r).
2. Calculate system power losses during each load level, total energy losses, bus voltages and total harmonic distortion at each bus for the case of nonlinear loads prior to capacitor installation.
3. Generate a set of initial feasible solution(s), forming the initial population (*pop*), randomly. Different types of moves as explained in the section of SA can be employed at this step.
4. Calculate the associated fitness value $f_v(s)$ of each solution.
5. Calculate the average fitness value $(f_v)_{avg}$ of the population. Also, calculate the probability selection of each individual (P_i) based on equation (4.3).

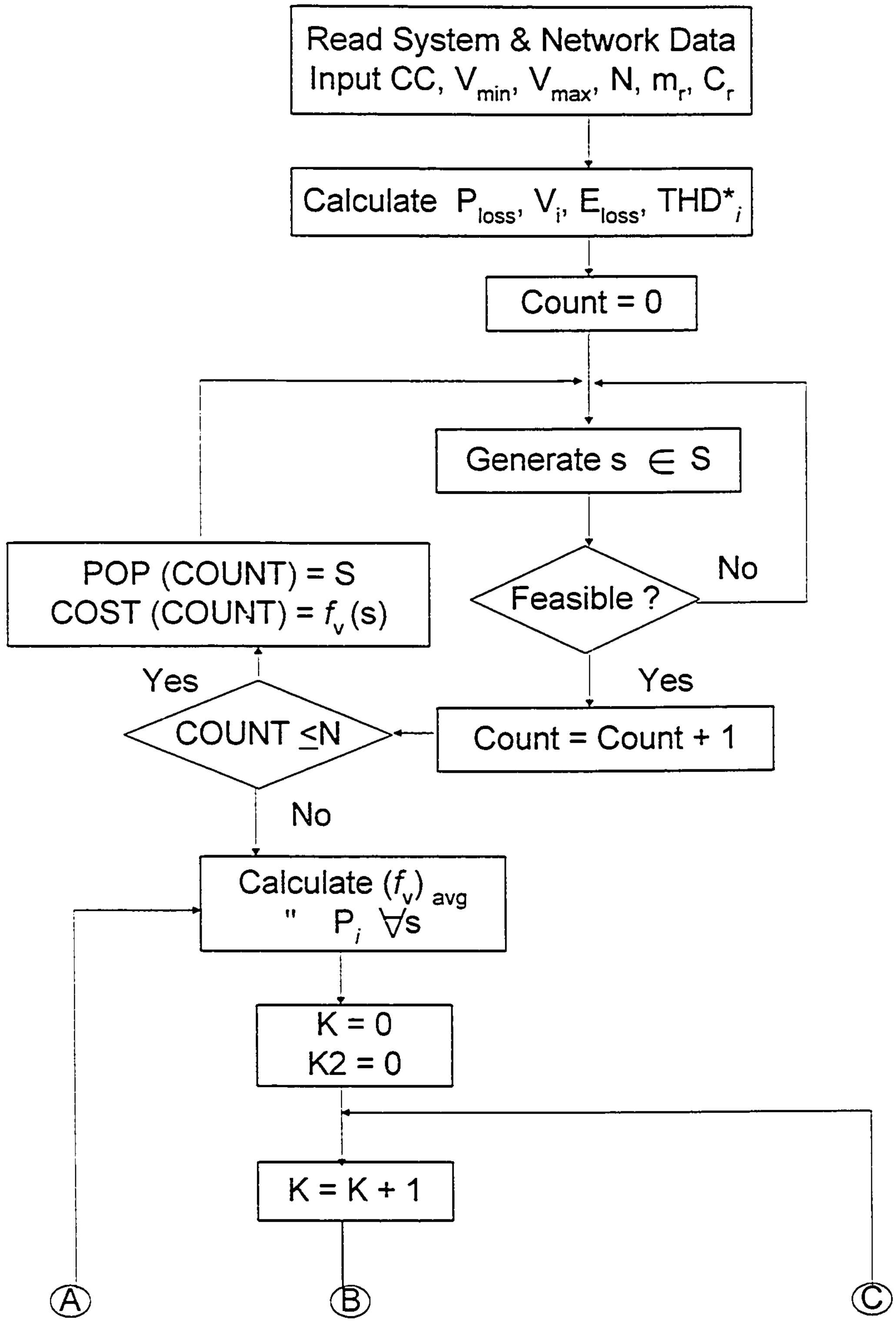
6. Transfer all individuals that fitness values are less than the calculated average fitness value to the next generation with no change.
7. Select one parent (*P1*) based on (P_i). Choose the other parent (*P2*) randomly. Apply crossover and mutation operators to generate a new offspring (*os*).
8. If (*os*) is not feasible go to 7, else go to 9.
9. Calculate the fitness value of the offspring $f_v(os)$.
10. Generated offspring is an individual in the new population replacing an individual that fitness value is greater than the calculated average fitness value.
11. Repeat steps (7) to (10) to find all remaining individuals.
12. Repeat steps (5) to (11) if the stopping criterion is not satisfied. Otherwise go to (13).
13. The best solution in the new population is the optimal solution.

4.2.5 GA features and shortcomings

In summary, the principal attractions of GA are:

1. Genetic algorithm is a multiple point search instead of single point search thereby identifying more peaks and reducing the probability of being trapped in local optima [15,18].
2. The algorithm is capable of searching for a global minima [30].
3. Many conventional optimization techniques rely on unrealistic assumptions of convexity, differentiability, linearity etc. None of these assumptions, however, are needed by a genetic algorithm [26].

4. GAs are inherently robust. They can cope with a diversity of problem types, high non-linear functions and different types of constraints [26].
5. Genetic algorithms, however, require tremendous computing time [30]. Moreover, tuning of the algorithm parameters to produce high quality solution is a difficult and a time-consuming task.



Read System & Network Data
Input CC, V_{min}, V_{max}, N, m_r, C_r
Calculate P_{loss}, V_i, E_{loss}, THD*$_i$
Count = 0
Generate s $\in$ S
Feasible ?
No
Yes
Count = Count + 1
COUNT $\leq$N
Yes
POP (COUNT) = S
COST (COUNT) = f_v(s)
No
Calculate $(f_v)_{avg}$
" P_i $\forall$s
K = 0
K2 = 0
K = K + 1
A
B
C

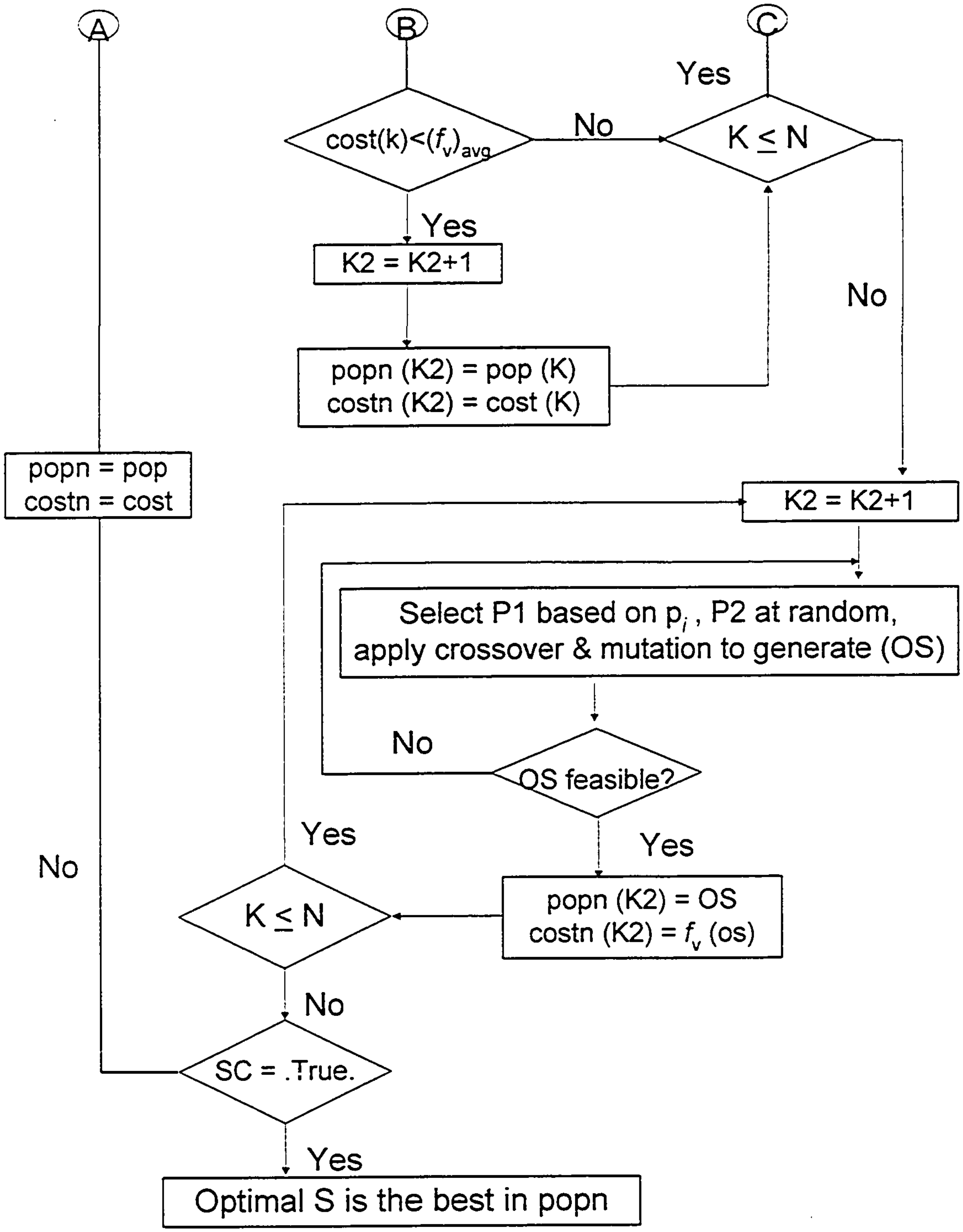


Figure 4.3 Genetic Algorithm Applied to CPP

4.3 Tabu search

This section introduces tabu search (TS) as a heuristic optimization method. First, the method is introduced. Then, a general framework of the method is outlined. In addition, the section explains how a TS-based algorithm is designed successfully. Moreover, it discusses the application of TS to solve the CPP in distribution systems.

4.3.1 Background

The modern form of Tabu Search (TS) was originally developed by Glover in 1977 [32]. TS is a powerful optimization procedure which has been successfully applied to a number of combinatorial optimization problems. The procedure is simple to implement and sufficiently versatile to incorporate problem-specific constraints [33,34].

TS is a form of neighborhood search. Each solution in the searching domain has a set of neighbors. A neighbor can be reached directly from the current solution by an operation or a perturbation mechanism called a 'move' [26]. TS is an iterative improvement procedure. It starts from an initial feasible solution and attempts to find a better one in the manner of a greatest-descent algorithm. Simple descent algorithms, however, are unidirectional and end at a local optimum. TS, unlike descent algorithms, is capable to continue exploration without becoming confounded by the absence of improving moves. Therefore, it does not fall into a local optimum [33,35].

The fundamental element underlying tabu search is the notion of exploiting certain forms of flexible memory to control the search process [26]. The focus on exploiting memory in TS, that is absent in both SA and GA, represents an obvious difference between TS and the other heuristic techniques. Historical records of the search process are stored in the flexible memory. History in TS determines which solutions may be reached by a move from the current solution. It helps investigate new solutions and provide means to escape local optima [26,33].

4.3.2 General framework

A simplified description of a typical tabu search technique is illustrated in Figure (4.4). TS starts with an initial solution. The initial solution is assumed to be the current best solution. Moves are employed to perturb the current solution in order to generate a new set of neighborhoods or 'trial solutions'. Each move generates a new trial solution. Based on fitness evaluation, the move generating the best trial solution is selected. The move is then checked if it is tabu (forbidden) or not. If not tabu, the move is accepted and the solution produced by this move is considered to be the current solution. If the move is tabu, however, its aspiration criterion is checked. If the move passes the aspiration criterion, then it is accepted and the associated solution becomes the current solution. Otherwise, the second best move is selected and the same procedure is repeated. If no new solution is found even after checking all the moves in the set, moves are regenerated to get another set of new solutions and the process is repeated. The algorithm is terminated if the stopping criteria are satisfied [32].

In light of the above procedure, one may determine the basic ingredients of TS. These include the initial sequence, mechanism for generating some neighborhood of the

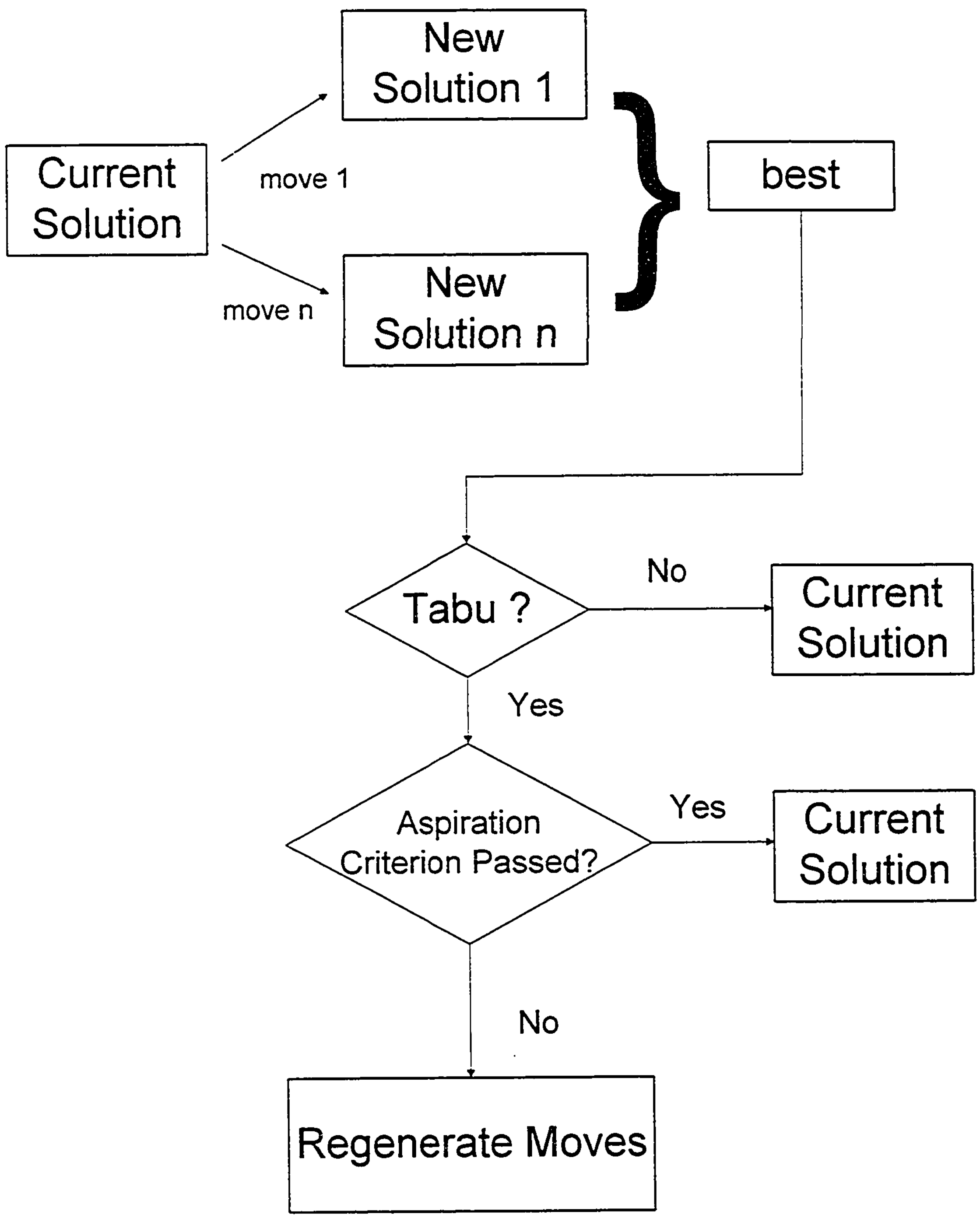


Figure 4.4 : Tabu Search Algorithm

current sequence, fitness measure, tabu restrictions, aspiration criterion and the stopping criterion [36].

The initial sequence is an initial feasible solution generated randomly or provided by some other heuristic technique. It represents the starting point of the algorithm. A perturbation mechanism is required by TS to generate some neighborhoods of a current solution. This can be achieved by defining a set of simple moves that add an element to or remove an element from the solution variables. Another simple move may be defined to exchange the values of two or more solution variables.

TS requires some fitness measure to compare among all generated neighborhoods. The better the fitness value of a solution, the more is the opportunity for it being chosen. The objective function itself may be used to provide such a measure. Sometimes, functions that approximate the objective function are utilized to provide the fitness measure.

The most basic form of TS consists of two key elements. The first, known as tabu restrictions, is constraining the search by classifying certain moves as forbidden (tabu). The second, known as aspiration criteria, is freeing the search by overriding the tabu status of moves where appropriate. These can be implemented by means of a short-term memory function [34,35].

The short-term memory component is the core of the TS procedure. It operates by selecting moves designed to progress quickly to a local optimum and then to go beyond the local optimum by making these moves forbidden or tabu. It is not of a concern in TS that the selected move improves the current solution. The selected move is the best in the set not classified as tabu, to drive the search into new unexplored regions [34].

The aspiration level criteria and tabu restrictions of TS play a dual role in constraining and guiding the search process. While aspiration criteria allow a move to be regarded admissible if they do apply, tabu restrictions allow a move to be regarded as admissible if they do not apply. This complementarity of the notions enables tabu restrictions and aspiration criteria to be integrated into a common framework [35].

During the search process, a solution that has been visited earlier may be visited again. In other words, cycling might take place. Tabu restrictions have the goal of avoiding cycling and driving the search to unexplored areas [26,28,36]. Tabu restrictions are implemented by using a tabu list consisting of the set of reverse of all moves classified as tabu [35]. A move is defined as tabu-active when its associated reverse move has occurred within a stipulated interval of recency in past moves. The tabu status of a move is the condition of being tabu-active or tabu-inactive [26]. The tabu list is characterized with a size usually represented as a fixed number. The tabu list size determines the number of iterations during which the tabu status of a move remains active before the move is released from the tabu list.

To enable a TS method to achieve its best performance levels, aspiration criteria are introduced to determine when tabu restrictions can be overridden [26,35]. The purpose of the aspiration criterion is to increase the flexibility of the algorithm and to speed up the search process. The simplest form of aspiration criterion is to override the tabu status of a move and consider it admissible when it leads to a better solution than the best visited so far [32,33].

As in SA and GA, a TS algorithm is terminated when the stopping criterion is satisfied. This can be achieved when a pre-specified number of iteration is elapsed or when no improvement is encountered in the optimal solution during a given number of successive iterations.

In advanced forms of TS, intermediate and long-term memory functions are added to the short-term memory function to achieve local intensification and global diversification of the search respectively [28,34]. Both recency-based and frequency-based tabu restrictions are utilized in this form of TS. Intensification and diversification strategies counterbalance and reinforce each other in TS. Intensification strategies undertake to create, aggressively, good solutions based on their objective function values. Diversification strategies, however, seek to generate new solutions that have not been encountered earlier to explore new regions in the searching domain [26]. Apart from these additional features of the advanced form of TS, simple TS proved to be very powerful in solving a variety of combinatorial optimization problems.

4.3.3 Design of a successful TS algorithm

Several decisions shall be properly made when a tabu-based solution algorithm is to be designed. If the design parameters of a TS algorithm are not selected appropriately, premature convergence with low quality solutions will result. In addition, the algorithm efficiency will be significantly affected.

Selection of the length of the tabu list can noticeably affect both the efficiency and the final solution quality obtained by the tabu search algorithm [33]. Many attributes of the solution space can affect the ideal tabu list size [28]. The appropriate list size is determined empirically by noting the occurrence of cycling when the size is too small and the quality of the solution when the size is too large [32]. It was found empirically that the tabu list size has a highly stable range of values which both prevent cycling and lead to remarkably good solutions [35]. When designing a TS algorithm, static and dynamic rules may be used to determine the proper list size. Static rules choose a value of the list size that remains fixed throughout the search. Dynamic rules, on the other hand, allow the list size to vary [26].

Some researchers reported that a considerable success has resulted when the tabu list size is kept as a fixed value. However, recent experimentation, carried out by some other researcher, discloses that better performance results by varying the tabu list size within a chosen interval of values [26,34].

In defining the moves of the TS algorithm, each solution in the space must be accessible to every other. This condition ensures that the neighborhoods cover every solution such that it is possible to find global optimum, given adequate time [33]. The algorithm designer may select among simple moves or compound moves consisting of two or more simple moves to generate neighborhood [26].

The number of moves to be executed at every iteration in TS is another important parameter to be judged by the designer. It depends on the problem under consideration. Usually, this number is determined empirically by trial and error process.

Some designers prefer to use the exact objective function to measure the relative attractiveness of the solutions. On the other hand, some other designers prefer to use approximate forms of the objective function that are easy to evaluate in order to enhance the algorithm's efficiency.

Another essential decision is related to the design of the tabu list. The designer shall select either to prevent moves from being reversed or to prevent them from being repeated. Sometimes, avoidance of both move reversal and move repetition may be employed. Avoiding move reversal was found to be more effective than avoiding move repetition [26,34].

The stopping criteria shall be tuned properly with the other parameters of TS algorithm to obtain an optimal solution of a high quality.

If the designer selects to work with an advanced TS algorithm, decisions related to the implementation of frequency-based tabu restrictions shall be properly made as well. A frequency counter represented by a fixed value must be designed to prevent a move from being selected if it has been selected for a given number of times, equivalent to the frequency counter, in the past.

4.3.4 Application of TS to the CPP in distribution systems

TS is a very powerful optimization tool. It can be applied to provide global or near-global optimal solutions to combinatorial optimization problems. When applied to the CPP in distribution systems, the following aspects were adopted.

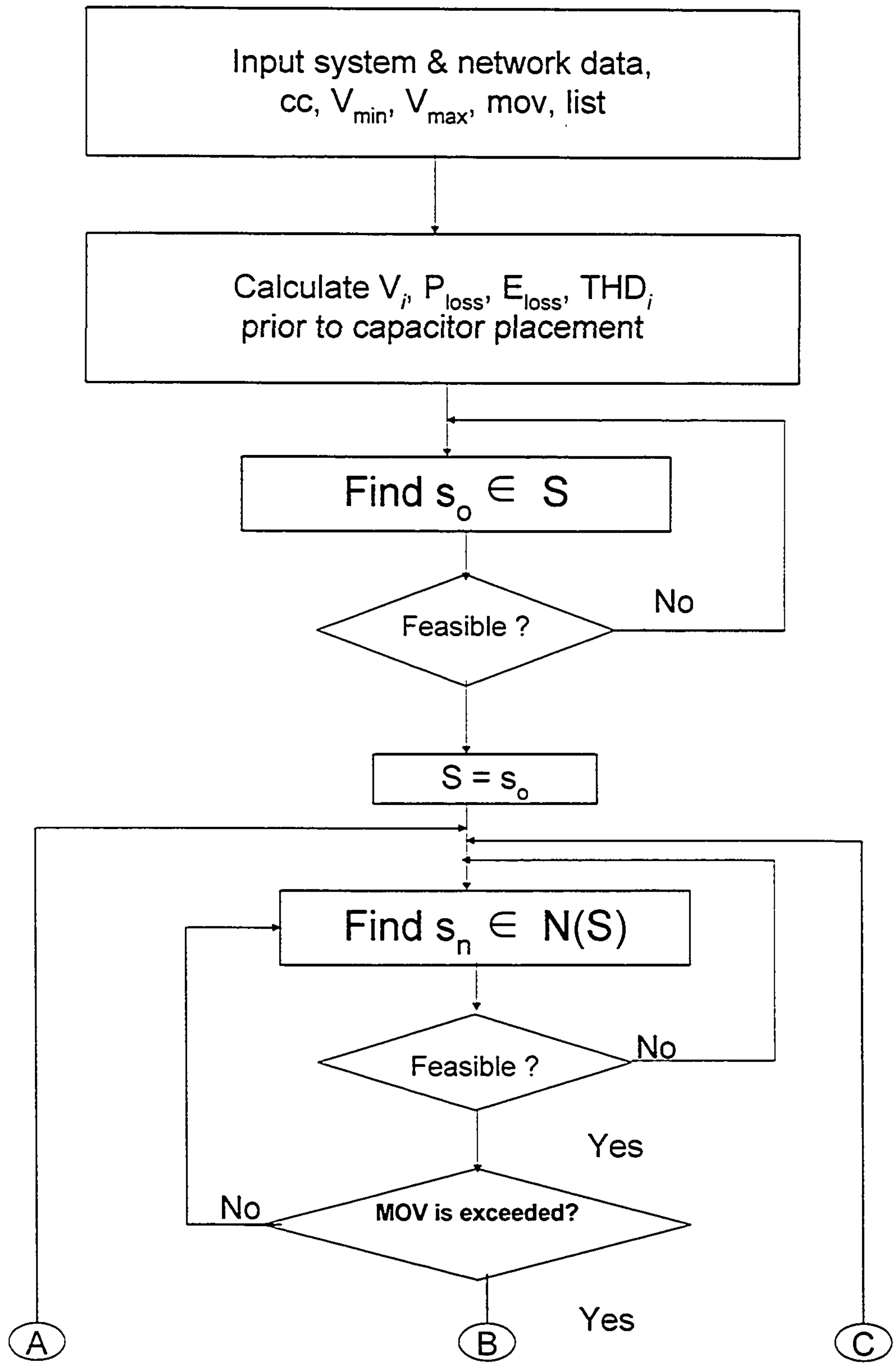
1. The algorithm is preceded by a sensitivity analysis providing a subset of buses which represent a set of candidate locations to install both fixed and switchable capacitors instead of considering all the buses in the network. The control settings of a switched capacitor installed at a particular bus during the peak load period are set higher than or equal to the settings during the medium load period. Similarly, capacitor control

settings during the medium load period are greater than or equal to the settings during the light load period. This assumption together with the sensitivity analysis are intended to reduce the searching domain and, hence, enhancing the algorithm efficiency.

2. The same moves defined in the section of SA are employed as perturbation mechanisms to generate neighborhoods of a current solution.
3. The tabu list size is maintained as a fixed value throughout the search process. It is determined empirically.
4. Only recency-based tabu restrictions are incorporated in the algorithm design. No frequency-based restrictions are considered.
5. The tabu list contains move reversals rather than move repetitions.
6. The number of moves in each iteration is kept as a constant value throughout the search process. It is determined empirically.
7. Exact formulation of the objective function is used to provide the relative attractiveness of the generated solutions.
8. Only feasible solutions are accepted. Therefore, no penalty factors are used to account for the case of infeasibility.
9. The algorithm will stop if no improvement in the optimal solutions is achieved during a given number of successive iterations. This is also determined empirically.

Based on the above remarks, tabu-based solution algorithm has been implemented to the CPP. The algorithm flowchart is illustrated in Figure (4.5). The algorithm procedure is summarized as follows:

1. Input system and network data, capacitor cost (cc), minimum allowable operating voltage ($V_{\min}$), maximum allowable operating voltage ($V_{\max}$) and tabu search parameters including number of moves per iteration (*mov*) and tabu list size (*list*).
2. Calculate bus voltages (V_i), power losses (P_{loss}), total energy losses during all load levels (E_{loss}) and total harmonic distortion at each bus (THD_i) for the case of nonlinear loads.
3. Begin TS algorithm with some initial solution s_o, from the Solution Space S. If not feasible, generate another solution at random. The initial solution is the current best solution.
4. Go through a sample set of candidate moves to generate neighborhood solutions S_n from the neighborhood structure of the current solution N(S).
5. Evaluate the current move. If the move produces a higher evaluation than any other so far found admissible, go to (6). Otherwise, go to (9).
6. Check tabu status. If the candidate move is tabu, go to (7). Otherwise, go to (8).
7. Check aspiration criterion (*AC*). If the move passes the aspiration criterion, go to (8). Otherwise, go to (9).
8. Move is admissible (store as new current best move).
9. Check sampling criteria, if another move in the list is to be examined, go to (5).
10. Make the chosen best move.
11. If the stopping criterion (*SC*) is not satisfied, update tabu list, tabu status and aspiration level. Else go to (4).
12. Print out the best solution found so far.


Input system & network data,
cc, V_{min}, V_{max}, mov, list
Calculate V_i, P_{loss}, E_{loss}, THD_i
prior to capacitor placement
Find $s_o \in S$
Feasible ?
No
$S = s_o$
Find $s_n \in N(S)$
Feasible ?
No
Yes
MOV is exceeded?
No
Yes
A
B
C

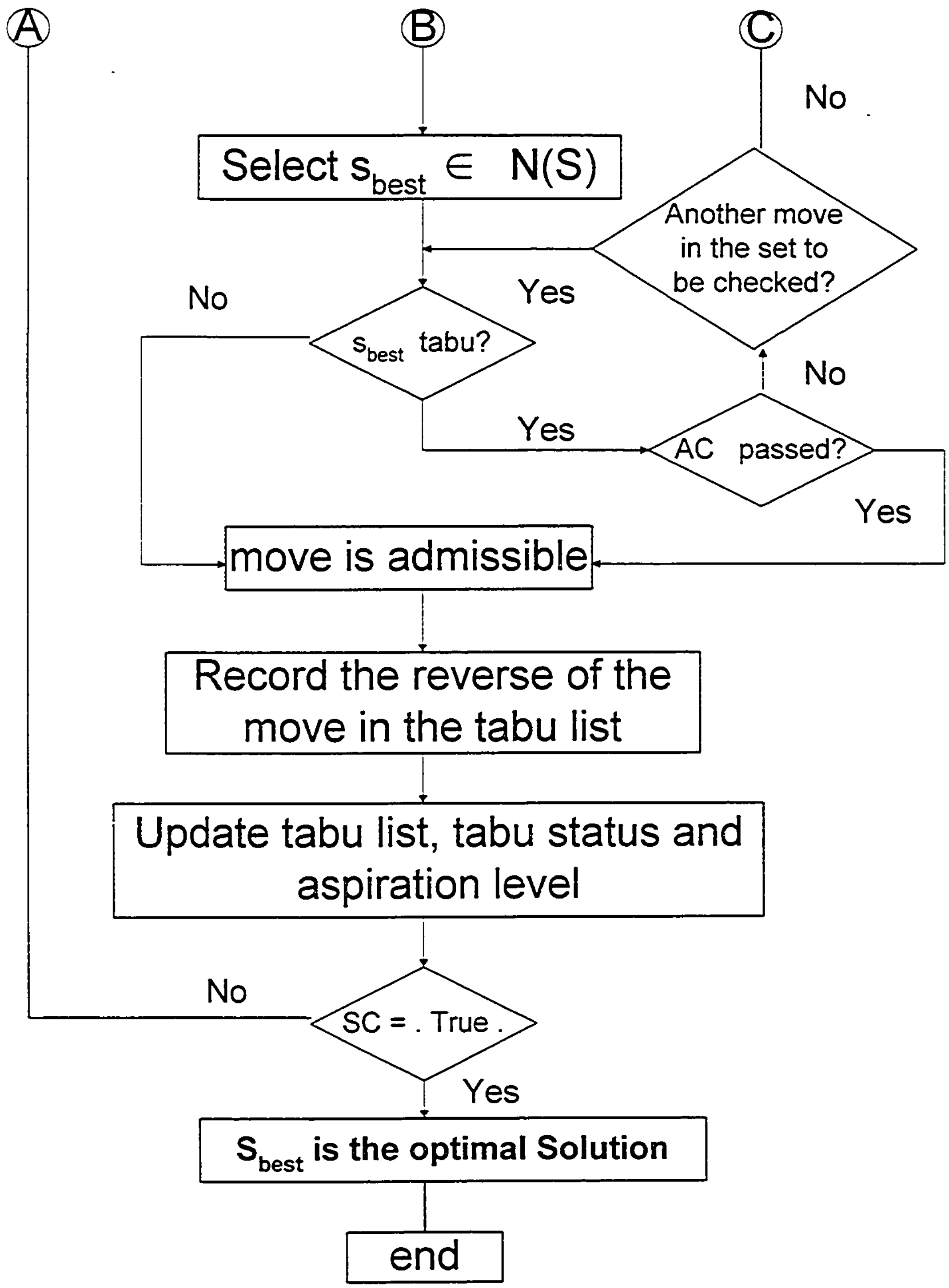


Figure 4.5 Tabu Search Applied to the CPP

4.4 Hybridization

Heuristic techniques that have been discussed above may be combined with each other to form a hybrid having advantages from each one of these heuristics. The efficiency of the new hybrid algorithm is expected to increase [26].

One way to form a hybrid algorithm is to start with a heuristic to give a fairly good feasible solution rather than starting completely at random. This solution will be considered as the initial solution from which the other heuristic, following the first one, will start the search for the optimal solution.

In the work of this thesis, a hybrid algorithm is formed by combining both GA and SA. The algorithm is referred to as GA-SA hybrid algorithm. GA is applied first to provide a good initial solution. Then, SA starts the search from this solution to find the optimal one.

Chapter 5

Test Systems & Simulation Results

This chapter presents the simulation results carried out using the optimization methodologies developed for solving the general CPP. A 69-bus radial distribution system and a 30-bus distribution system containing a loop have been selected as Test System-1 and Test System-2 respectively. For each system, simulation results obtained from application of simulated annealing, genetic algorithm, tabu search and a hybrid GA-SA algorithm are presented and compared.

5.1 Test system-1 & data

Figure (5.1) shows the one line diagram of the test system. The test system is a 12.66 kV, 10 kVA, 69-bus radial distribution feeder consisting of one main branch and seven laterals containing different number of load buses. Buses 1 to 27 lie on the main branch. Bus # 1 represents the substation feeding the distribution system. [6]

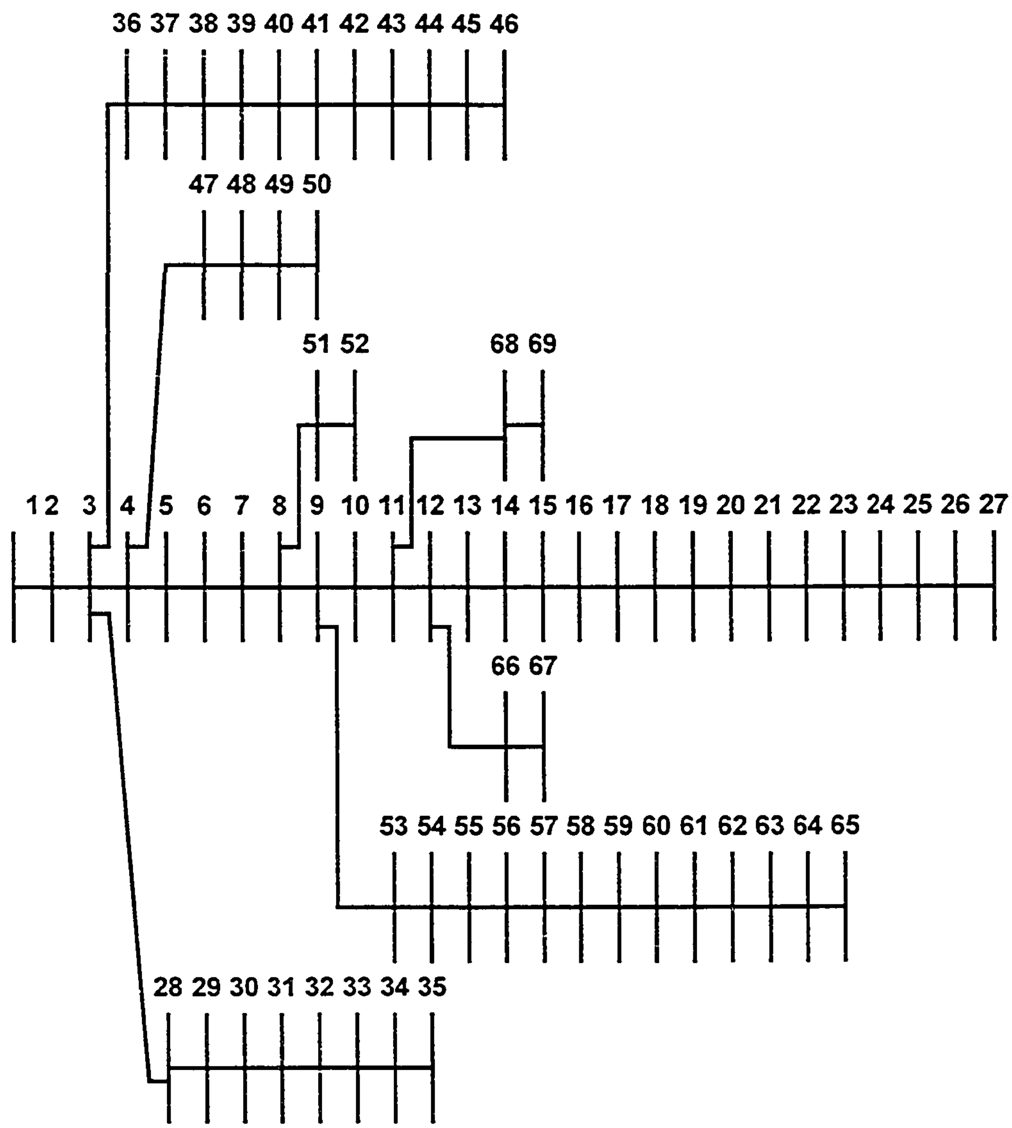


Figure 5.1: Shematic diagram of a 69-bus test system

Table (5.1) shows the network data for this system. A feeder segment is modeled by the series combination of its corresponding resistance and reactance.

Loads are represented as power sink where constant values of active power (P) and reactive power (Q) are assumed. Table (5.2) shows the corresponding P and Q for the loads connected to each bus.

As stated earlier, nonlinear loads are included in the formulation of the CPP to study their effect on the optimal solution. For this, some of the buses are assumed to have nonlinear loads. Table (5.3) lists the buses to which nonlinear loads are connected together with the respective nonlinear load percentages.

To account for load variation in the system, three different load levels are considered. They are classified as light, medium and peak. Load duration data assumed for the system are shown in Table (5.4).

Table (5.5) shows the maximum harmonic order (N), the minimum per-unit voltage (V_{min}), the maximum per-unit voltage (V_{max}), the maximum allowable total harmonic distortion (THD_{max}) and the maximum number of capacitor banks to be installed at one location $(l_k)_{max}$. It also shows the energy cost per unit (k_e) and other cost figures defined as follows:

CFIC : Capacitor Fixed Installation Cost

CPC : Capacitor Purchase Cost

CBS : Capacitor Bank Size

Prior to the application of the techniques to solve the CPP for a distribution system, a sensitivity analysis has been carried out to select a subset of candidate buses for capacitor installation. The aim of this is to enhance the efficiency of the solution algorithms without

Table 5.1 - Test System-1: Network Data

From	To	R (ohm)	X (ohm)	From	To	R (ohm)	X (ohm)	From	To	R (ohm)	X (ohm)
1	2	0.0005	0.0012	24	25	0.7488	0.2475	47	48	0.0851	0.2083
2	3	0.0005	0.0012	25	26	0.3089	0.1021	48	49	0.2898	0.7091
3	4	0.0015	0.0036	26	27	0.1732	0.0572	49	50	0.0822	0.2011
4	5	0.0251	0.0294	3	28	0.0044	0.0108	8	51	0.0928	0.0473
5	6	0.3660	0.1864	28	29	0.0640	0.1565	51	52	0.3319	0.1114
6	7	0.3811	0.1941	29	30	0.3978	0.1315	9	53	0.1740	0.0886
7	8	0.0922	0.047	30	31	0.0702	0.0232	53	54	0.2030	0.1034
8	9	0.0439	0.0251	31	32	0.3510	0.1160	54	55	0.2842	0.1447
9	10	0.819	0.2707	32	33	0.8390	0.2816	55	56	0.2813	0.1433
10	11	0.1872	0.0619	33	34	1.708	0.5646	56	57	1.590	0.5337
11	12	0.7114	0.2351	34	35	1.474	0.4873	57	58	0.7837	0.263
12	13	1.030	0.340	3	36	0.0044	0.0108	58	59	0.3042	0.1006
13	14	1.044	0.345	36	37	0.0640	0.1565	59	60	0.3861	0.1172
14	15	1.058	0.3496	37	38	0.1053	0.1230	60	61	0.5075	0.2585
15	16	0.1966	0.065	38	39	0.0304	0.0355	61	62	0.0975	0.0496
16	17	0.3744	0.1238	39	40	0.0018	0.0021	62	63	0.145	0.0738
17	18	0.0047	0.0016	40	41	0.7283	0.8509	63	64	0.7105	0.3619
18	19	0.3276	0.1083	41	42	0.3100	0.3623	64	65	1.041	0.5302
19	20	0.2106	0.0696	42	43	0.041	0.0478	11	66	0.2012	0.0611
20	21	0.3416	0.1129	43	44	0.0092	0.0116	66	67	0.0047	0.0014
21	22	0.014	0.0046	44	45	0.1089	0.1373	12	68	0.7394	0.2444
22	23	0.1591	0.0526	45	46	0.0009	0.0012	68	69	0.0047	0.0016
23	24	0.3463	0.1145	4	47	0.0034	0.0084				

Table 5.2 - Test System-1: Load Data

Bus #	P(kW)	Q(kVar)	Bus #	P(kW)	Q(kVar)	Bus #	P(kW)	Q(kVar)
1	0	0	24	28	20	47	0	0
2	0	0	25	0	0	48	79	56.4
3	0	0	26	14	10	49	384.7	274.5
4	0	0	27	14	10	50	384.7	274.5
5	0	0	28	26	18.6	51	40.5	28.3
6	2.6	2.2	29	26	18.6	52	3.6	2.7
7	40.4	30	30	0	0	53	4.35	3.5
8	75	54	31	0	0	54	26.4	19
9	30	22	32	0	0	55	24	17.2
10	28	19	33	14	10	56	0	0
11	145	104	34	19.5	14	57	0	0
12	145	104	35	6	4	58	0	0
13	8	5.5	36	26	18.55	59	100	72
14	8	5.5	37	26	18.55	60	0	0
15	0	0	38	0	0	61	1244	888
16	45.5	30	39	24	17	62	32	23
17	60	35	40	24	17	63	0	0
18	60	35	41	1.2	1	64	227	162
19	0	0	42	0	0	65	59	42
20	1	0.6	43	6	4.3	66	18	13
21	114	81	44	0	0	67	18	13
22	5.3	3.5	45	39.22	26.3	68	28	20
23	0	0	46	39.22	26.3	69	28	20

Table 5.3 - Test System-1: Buses of Nonlinear Loads

Bus #	**w_i (%)**
5	20
14	10
20	10
30	20
39	30
50	40
61	30
64	50

Table 5.4 - Test System-1: Load Duration Data

	Load Level		
	Peak	Medium	Light
S	1.0	0.8	0.5
Duration (hrs)	1000	6760	1000

Table 5.5 : Cost and Other Pertinent Data

Parameter	Value
N	11
V_{min}	0.93 pu
V_{max}	1.05 pu
THD_{max}	5 %
$(l_k)_{max}$	4 banks
k_e	0.06 $/kWh
CFIC	1000 $
CPC	900 $/bank
CBS	300 kVar

Table 5.6 - Test System-1: Sensitivity Factors (SF) of the Buses

Bus #	SF*10^5	Bus #	SF*10^5	Bus #	SF*10^5
1	0	24	13.887	47	0.0287
2	0.016	25	13.899	48	0.0367
3	0.024	26	13.901	49	0.0377
4	0.129	27	0.0175	50	3.64
5	1.66	28	0.0246	51	3.643
6	3.25	29	0.0611	52	3.90
7	3.64	30	0.0648	53	3.972
8	3.83	31	0.070	54	4.068
9	6.78	32	0.753	55	4.1575
10	7.44	33	0.083	56	4.657
11	9.25	34	0.085	57	4.900
12	10.85	35	0.0413	58	4.9913
13	12.45	36	0.394	59	5.098
14	12.53	37	0.971	60	5.231
15	12.83	38	1.136	61	5.24
16	13.387	39	1.144	62	5.249
17	13.392	40	3.79	63	5.2771
18	13.553	41	4.91	64	5.286
19	13.653	42	5.06	65	7.643
20	13.809	43	5.09	66	7.645
21	13.813	44	5.44	67	9.971
22	13.827	45	5.442	68	9.974
23	13.849	46	0.025	69	0.02179

jeopardizing the quality of the solution obtained. The most sensitive buses, characterized by high sensitivity factors, are selected. Table (5.6) shows the sensitivity factors obtained from the sensitivity analysis of the network buses. Based on the sensitivity analysis results and other engineering judgments as explained in section 3.3, ten buses have been selected to form the set N_C. These buses are bus # 8, 11, 12, 21, 48, 49, 50, 59, 61 and 64.

5.2 Test system-1 conditions prior to capacitor placement

Prior to capacitor installation, a load flow program based on Gauss-Seidel iterative method was run to obtain the present system conditions. System conditions are shown in Table (5.7). The table specifies the minimum per-unit bus voltage, maximum per-unit bus voltage, real power losses in kW and the cost of energy losses during all load levels. It is clear from the table that the minimum bus voltages during both the medium and the peak load levels are less than the pre-specified minimum allowable bus voltage. Therefore, capacitors shall be installed to provide the required voltage correction and to reduce the overall energy losses in the system.

System conditions without capacitor placement, if nonlinear loads are considered, are shown in Table (5.8). In comparison with Table (5.7) where all the loads are assumed to be linear, it can be seen that system minimum and maximum bus voltages have increased slightly due to the addition of harmonic voltages in calculating the overall rms bus voltages as given in equation (3.8). In addition, real power losses during all the load levels and hence the total cost of energy losses in the system have increased because of the harmonic currents injected by the nonlinear loads into the system.

Table 5.7 - Test System-1: System Conditions prior to Capacitor Placement (Linear loads only)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9569	0.9290	0.9094
Maximum Bus Voltage (pu)	1.000	1.000	1.000
Real Power Losses (KW)	50.4991	137.1431	222.5266
Cost of Energy Losses ($)	3029.9470	55625.230	13351.590
Total Cost of Energy Losses = 72006.770 $			

Table 5.8 - Test System-1: System Conditions prior to Capacitor Placement (Both Linear & non-linear loads)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9573	0.9295	0.9099
Maximum Bus Voltage (pu)	1.0005	1.0006	1.0006
Maximum THD (%)	3.419	3.792	3.884
Real Power Losses (KW)	50.6559	138.2789	223.8575
Cost of Energy Losses ($)	3039.3550	56085.930	13431.450
Total Cost of Energy Losses = 72556.73 S			

Simulation results for this case show that the maximum total harmonic distortion in the system during every load level is below the specified limit of 5%.

5.3 Simulation results for test system-1

The proposed solution methodologies have been implemented in FORTRAN-77. A 133 MHz PC was used to execute the programs. Three different cases were studied as described underneath:

- Case I : With fixed capacitor placement and linear loads
- Case II : With both fixed and switched capacitor placement and linear loads
- Case III : With both fixed and switched capacitor placement and both linear and nonlinear loads

The aim is to determine which option is more economical either by using fixed capacitors only or by using both fixed and switched capacitors. Another objective is to study the effect of nonlinear loads on the optimal solution of the CPP.

5.3.1 Test system-1 : simulation results obtained for Case-I

Different solution algorithms based on SA, GA,TS and a hybrid GA-SA algorithm have been designed to find the optimal solution for this case. In this case, only fixed type capacitors can be installed in the system and all the loads are assumed to be linear. Computer programs have been written for these algorithms based on the respective procedures highlighted earlier.

Table (5.9) shows the design parameters of SA algorithm applied to solve for the optimal solution of this case. The parameters are defined as follows:

T_o : System initial temperature

Ar_o : Initial Acceptance ratio

M : Number of moves per iteration/temperature

C_f : Cooling factor

S_c : The algorithm will stop if no improvement is encountered in the optimal solution during the last S_c consecutive iterations/temperatures.

These parameters are set empirically by trial and error procedure. It shall be noted here that proper selection of these parameters is a very time consuming task. Probably, it is the most difficult part in the design of the algorithm.

Table (5.10) shows the optimal solution obtained by the SA algorithm designed with the parameters in Table (5.9). The solution calls for a 300 kVar fixed capacitor to be installed at bus # 21 and a 1200 kVar fixed capacitor to be installed at bus # 61.

System conditions with capacitors placed as per the optimal solution are given in Table (5.11). As expected, capacitors have regulated the system voltages at the medium and peak load levels to lie within the upper and lower voltage limits specified in Table (5.5). Also, real power losses have been reduced as a result of capacitor installation. Consequently, the total cost of energy losses has been reduced.

Considering the system cost prior to capacitor placement and the system cost after capacitor placement, it can be concluded that a net savings of 17028.44 $ has been

Table 5.9 - Test System-1: SA Design Parameters (Case-I)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	13000	0.8	5	0.85	15

Table 5.10 - Test System-1: Optimal Solution Using SA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
21	300	300	300
61	1200	1200	1200

Table 5.11 - Test System-1: System Conditions with the Optimal Solution by SA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9751	0.9486	0.930
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	46.4877	91.1998	144.9337
Cost of Energy Losses ($)	2780.260	36990.64	8698.422
Total Cost of Energy Losses = 48478.33 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54978.33 $			

achieved. The net saving is calculated by subtracting the total system cost with capacitor placement from the total system cost prior to capacitor placement.

Secondly, Table (5.12) shows the design parameters of the GA algorithm applied to obtain the optimal solution of this case. The parameters are defined as shown below:

P_s : Population Size

M_r : Mutation rate

C_r : Crossover rate

G : No. of generations before algorithm is terminated

Again, the parameters are set empirically by trial and error procedure. Parameters that have resulted in the best solution were chosen. A genetic algorithm designed based on steady-state replacement usually converges faster than the one designed based on generational replacement. Due to this, steady-state replacement method requires less number of generations before it converges to the optimal solution.

With these parameters, the optimal solution obtained is as shown in Table (5.13). A 300 kVar fixed capacitor is to be installed at bus # 21 and a 1200 kVar fixed capacitor is to be installed at bus # 61.

Table (5.14) shows the system conditions when capacitor placement is implemented as per the optimal solution. As can be seen from the table, the required voltage regulation at the medium and the peak load levels has been attained. In addition, energy loss reductions at different load levels have been achieved. The cost of the optimal solution obtained here is the same as the one obtained by SA.

Table 5.12 - Test System-1: GA Design Parameters (Case-I)

Parameter	Ps	M_r	G	C_r
Design Value	30	0.1	20	1.0

Table 5.13 - Test System-1: Optimal Solution Using GA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
21	300	300	300
61	1200	1200	1200

Table 5.14 - Test System-1: System Conditions with the Optimal Solution by GA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9751	0.9486	0.930
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	46.4877	91.1998	144.9337
Cost of Energy Losses ($)	2780.260	36990.64	8698.422
Total Cost of Energy Losses = 48478.33 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54978.33 $			

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.15) shows the algorithm parameters which are defined hereunder:

T_s : Tabu list size

V : Number of moves in each iteration

I_t : Number of consecutive iterations, during which no improvement is achieved in the optimal solution, allowed before the algorithm is terminated.

As in the cases of SA and GA algorithms, parameters of the TS algorithms are set empirically. The optimal solution with these parameters is shown in Table (5.16). The solution is identical to the one obtained by SA and GA. System conditions with the optimal solution are given in Table (5.17) where the same net savings achieved by SA and GA are achieved by TS as well.

Finally, a hybrid algorithm has been designed by combining both GA and SA. The algorithm is referred to as GA-SA algorithm. In this hybrid algorithm, GA is applied first to obtain a fairly good feasible solution. This solution is used as the initial solution for the SA algorithm in its search for the optimal solution.

Design parameters of the GA-SA algorithm for this case are given in Table (5.18). These parameters are determined empirically. An identical solution to those obtained by SA, GA and TS algorithms is obtained here by applying the GA-SA algorithm as shown in Table (5.19). System conditions with the optimal solution are given in Table (5.20).

Table 5.15 - Test System-1: TS Design Parameters (Case-I)

Parameter	T_s	V	I_t
Design Value	16	3	40

Table 5.16 - Test System-1: Optimal Solution Using TS (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
21	300	300	300
61	1200	1200	1200

Table 5.17 - Test System-1: System Conditions with the Optimal Solution by TS (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9751	0.9486	0.930
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	46.4877	91.1998	144.9337
Cost of Energy Losses ($)	2780.260	36990.64	8698.422
Total Cost of Energy Losses = 48478.33 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54978.33 $			

Table 5.18 - Test System-1: GA-SA Design Parameters (Case-I)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	1000	0.83	6	0.90	15	6	0.15	2	1.0

Table 5.19 - Test System-1: Optimal Solution Using GA-SA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
21	300	300	300
61	1200	1200	1200

Table 5.20 - Test System-1: System Conditions with the Optimal Solution by GA-SA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9751	0.9486	0.930
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	46.4877	91.1998	144.9337
Cost of Energy Losses ($)	2780.260	36990.64	8698.422
Total Cost of Energy Losses = 48478.33 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54978.33 $			

5.3.2 Test system-1 : simulation results obtained for Case-II

Case-II involves the use of both fixed and switched capacitors. Loads are assumed to be linear. Different solution algorithms based on SA, GA,TS and a hybrid GA-SA algorithm have been designed to find the optimal solution for this case. Computer programs have been written in FORTRAN-77 for these algorithms based on the respective procedures highlighted earlier.

Table (5.21) shows the SA design parameters for this case which have been determined empirically. With these parameters, the optimal solution is as shown in Table (5.22). A 300 kVar switched capacitor is to be placed at bus # 12. It is to be switched on during both the medium and peak load levels and to be switched off during the light load level. Another 1200 kVar switched capacitor needs to be installed at bus # 61. Three banks are to be switched on to give 900 kVar during both the light and the medium load levels. The fourth bank is to be switched on only during the peak load level to supply a total of 1200 kVar to the system.

Table (5.23) shows the system conditions with capacitors placed according to the optimal solution. It is clear from the table that system voltages have been regulated to lie within the acceptable range. More reductions in the cost of the energy losses during different load levels have been achieved as compared to case-I with fixed capacitors only. A net savings of 17699.30 $ is achieved when this solution is applied.

Secondly, a GA-based solution algorithm has been designed for this case. Table (5.24) shows the design parameters of the GA algorithm obtained experimentally to get the best results. With these parameters, the optimal solution obtained is as shown in Table

Table 5.21 - Test System-1: SA Design Parameters (Case-II)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	33000	1.00	7	0.85	15

Table 5.22 - Test System-1: Optimal Solution Using SA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
12	0	300	300
61	900	900	1200

Table 5.23 - Test System-1: System Conditions with the Optimal Solution by SA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9702	0.9442	0.9300
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Read Power Losses (KW)	36.8803	90.8074	146.0526
Cost of Energy Losses ($)	2212.8190	36831.50	8763.154
Total Cost of Energy Losses = 47807.470 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54307.47 $			

(5.25). A 600 kVar fixed capacitor is to be installed at bus # 12 and a 1200 kVar switched capacitor is to be installed at bus # 61. Two banks are to be switched on to give 600 kVar during the light load level. Three banks are to be switched on to give 900 kVar during the medium load level. The fourth bank is to be switched on only during the peak load level to supply a total of 1200 kVar to the system.

Table (5.26) shows the system conditions with capacitors placed as per the optimal solution. As can be seen from the table, required voltage regulation has been attained. With this solution, we have achieved a net savings of 17157.30 $.

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.27) contains the empirically- set algorithm parameters. The optimal solution with these parameters is shown in Table (5.28). A 300 kVar fixed capacitor is to be placed at bus # 21 and a 1200 kVar switched capacitor needs to be installed at bus # 61. Three banks of the switched capacitor are to be switched on to give 900 kVar during the light load level. The fourth bank is to be switched on during both the medium and the peak load levels to supply a total of 1200 kVar to the system.

Table (5.29) shows the system conditions when the optimal solution is implemented. The solution obtained by TS is even closer to the one obtained by SA than the one obtained by GA. With this solution, a net savings of 17598.12 $ has been achieved.

Finally, a GA-SA hybrid algorithm has been designed to find the optimal solution for this case. Design parameters of the GA-SA algorithm for this case are given in Table (5.30). These parameters are determined empirically. Table (5.31) shows the optimal solution obtained with these parameters. A 300 kVar switched capacitor shall be placed at bus # 21. It is to be switched on during both the medium and peak load levels and to be

Table 5.24 - Test System-1: GA Design Parameters (Case-II)

Parameter	Ps	M_r	G	C_r
Design Value	32	0.08	20	1.0

Table 5.25 - Test System-1: Optimal Solution Using GA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
12	600	600	600
61	600	900	1200

Table 5.26 - Test System-1: System Conditions with the Optimal Solution by GA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9678	0.9452	0.931
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	34.9342	90.429	144.5901
Cost of Energy Losses ($)	2096.054	36678.01	8675.407
Total Cost of Energy Losses = 47449.47 $			
Installation Cost of Capacitors = 7400 $			
Total System Cost = 54849.47 $			

Table 5.27 - Test System-1: TS Design Parameters (Case-II)

Parameter	T_s	V	I_t
Design Value	13	7	10

Table 5.28 - Test System-1: Optimal Solution Using TS (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
21	300	300	300
61	900	1200	1200

Table 5.29 - Test System-1: System Conditions with the Optimal Solution by TS (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9711	0.9486	0.930
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	36.9930	91.1998	144.9337
Cost of Energy Losses ($)	2219.580	36990.64	8698.422
Total Cost of Energy Losses = 47908.65 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 54408.65 $			

switched off during the light load level. Another 1200 kVar switched capacitor needs to be installed at bus # 61. Two banks are to be switched on to give 600 kVar during the light load level. Three banks are to be switched on to give 900 kVar during the medium load level. The fourth bank is to be switched on only during the peak load level to supply a total of 1200 kVar to the system.

System conditions with the optimal solution are given in Table (5.32). When compared to the original system without capacitor placement, we have achieved a net savings of 18033.82 $.

Table 5.30 - Test System-1: GA-SA Design Parameters (Case-II)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	3000	1.0	5	0.92	30	6	0.10	3	1.0

Table 5.31 - Test System-1: Optimal Solution Using GA-SA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
21	0	300	300
61	600	900	1200

Table 5.32 - Test System-1: System Conditions with the Optimal Solution by GA-SA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9659	0.9442	0.9300
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Read Power Losses (KW)	34.8185	90.4473	144.9737
Cost of Energy Losses ($)	2089.109	36685.42	8698.422
Total Cost of Energy Losses = 47472.95 $			
Installation Cost of Capacitors = 6500 $			
Total System Cost = 53972.95 $			

5.3.3 Test system-1 : simulation results obtained for Case-III

Case-III involves the use of both fixed and switched type capacitors. Both linear and nonlinear loads are assumed for this case. Different solution algorithms based on SA, GA, TS and a hybrid GA-SA algorithm have been designed. In this case. Computer programs have been written for these algorithms based on the respective procedures highlighted earlier.

System conditions before capacitor placement are shown in Table (5.8). Table (5.33) shows the SA design parameters for this case which have been determined empirically. With these parameters, the optimal solution is as shown in Table (5.34). It can be seen that the inclusion of nonlinear loads in the problem formulation has contributed to a dramatic change in the optimal solution. Fixed and switched capacitors need to be installed at six different places. The solution can be summarized as follows:

1. A 1200 kVar switched capacitor shall be placed at bus # 8. During the light load level, the capacitor is switched to give 600 kVar only. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.
2. A 300 kVar switched capacitor shall be placed at bus # 21. During the light load level, the capacitor is switched off. However, it shall be switched on during both the medium and the peak load levels.
3. A 1200 kVar switched capacitor shall be placed at bus # 48. During the light load level, the capacitor is switched to give 900 kVar only. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.
4. A 300 kVar fixed capacitor shall be placed at bus # 49.

Table 5.33 - Test System-1: SA Design Parameters (Case-III)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	100	0.53	15	0.88	8

Table 5.34 - Test System-1: Optimal Solution Using SA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
8	600	1200	1200
21	0	300	300
48	900	1200	1200
49	300	300	300
59	0	0	300
61	900	900	1200

Table 5.35 - Test System-1: System Conditions with the Optimal Solution Using SA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9724	0.9489	0.9386
Maximum Bus Voltage (pu)	1.0013	1.0015	1.0014
Maximum THD (%)	3.050	4.582	4.832
Read Power Losses (KW)	38.8016	93.8898	150.9984
Cost of Energy Losses ($)	2328.095	38081.7	9059.9010
Total Cost of Energy Losses = 49469.7 $			
Installation Cost of Capacitors = 19500 $			
Total System Cost = 68969.70 $			

5. A 300 kVar switched capacitor shall be placed at bus # 59. During both the light and the medium load levels, the capacitor is switched off. However, it shall be switched to give 300 kVar during the peak load level.
6. A 1200 kVar switched capacitor shall be placed at bus # 61. During both the light and the medium load levels, the capacitor is switched to give 900 kVar. However, it shall be switched to give 1200 kVar during the peak load level.

Table (5.35) shows the system conditions with capacitors placed according to the optimal solution. It is clear from the table that system voltages have been regulated to be within the acceptable range. However, less reductions in the cost of the energy losses during different load levels have been achieved due to the confinement of harmonic distortion in the problem formulation. Savings of 3587.03 $ have been achieved when this solution is applied.

Secondly, a GA-based solution algorithm has been designed for this case. Table (5.36) shows the design parameters of the GA algorithm obtained experimentally to get the best results. With these parameters, the optimal solution obtained is as shown in Table (5.37). Fixed and switched capacitors need to be installed at five different places. The solution can be summarized as follows:

1. A 1200 kVar switched capacitor shall be placed at bus # 8. During the light load level, the capacitor is switched to give 900 kVar only. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.
2. A 600 kVar fixed capacitor shall be placed at bus # 12.

3. A 900 kVar switched capacitor shall be placed at bus # 48. During the light load level, the capacitor is switched to give 300 kVar. However, it shall be switched to give 900 kVar during both the medium and the peak load levels.
4. A 900 kVar switched capacitor shall be placed at bus # 49. During the light load level, the capacitor is switched off. However, it shall be switched to give 900 kVar during both the medium and the peak load levels.
5. A 1200 kVar switched capacitor shall be placed at bus # 61. The capacitor is switched to give 600 kVar, 900 kVar and 1200 kVar during the light, medium and peak load levels respectively.

Table (5.38) shows the system conditions with capacitors placed as per the optimal solution. As can be seen from the table, required voltage regulation has been attained. With this solution, we have achieved a net savings of 1581.75 $.

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.39) contains the empirically- set algorithm parameters. The optimal solution with these parameters is shown in Table (5.40). Fixed and switched capacitors need to be installed at five different places. The solution is summarized as follows:

1. A 900 kVar switched capacitor shall be placed at bus # 11. During both the light and the medium load levels, the capacitor is switched to give 300 kVar only. However, it shall be switched to give 900 kVar during the peak load level.
2. A 900 kVar switched capacitor shall be placed at bus # 48. During the light load level, the capacitor is switched to give 600 kVar only. However, it shall be switched to give 900 kVar during both the medium and the peak load levels.

Table 5.36 - Test System-1: GA Design Parameters (Case-III)

Parameter	Ps	M_r	G	C_r
Design Value	20	0.2	15	1.0

Table 5.37 - Test System-1: Optimal Solution Using GA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
8	900	1200	1200
12	600	600	600
48	300	900	900
49	0	900	900
61	600	900	1200

Table 5.38 - Test System-1: System Conditions with the Optimal Solution Using GA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9711	0.9496	0.9359
Maximum Bus Voltage (pu)	1.0006	1.0027	1.0018
Maximum THD (%)	3.940	3.817	4.932
Read Power Losses (KW)	41.8661	98.5716	151.3725
Cost of Energy Losses ($)	2511.964	39980.66	9082.352
Total Cost of Energy Losses = 51574.98 $			
Installation Cost of Capacitors = 19400 $			
Total System Cost = 70974.98 $			

Table 5.39 - Test System-1: TS Design Parameters (Case-III)

Parameter	T_s	V	I_t
Design Value	13	4	40

Table 5.40 - Test System-1: Optimal Solution Using TS (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
11	300	300	900
48	600	900	900
50	900	900	1200
59	600	600	600
61	900	900	900

Table 5.41 - Test System-1: System Conditions with the Optimal Solution Using TS (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9783	0.9524	0.9361
Maximum Bus Voltage (pu)	1.0048	1.0039	1.0049
Maximum THD (%)	2.999	4.559	4.819
Read Power Losses (KW)	58.7048	98.8474	151.4569
Cost of Energy Losses ($)	3522.29	40092.50	9087.4140
Total Cost of Energy Losses = 52702.20 $			
Installation Cost of Capacitors = 18500 $			
Total System Cost = 71202.20 $			

3. A 1200 kVar switched capacitor shall be placed at bus # 50. During both the light and the medium load levels, the capacitor is switched to give 900 kVar only. However, it shall be switched to give 1200 kVar during the peak load level.
4. A 600 kVar fixed capacitor shall be placed at bus # 59.
5. A 900 kVar fixed capacitor shall be placed at bus # 61

Table (5.41) shows the system conditions when the optimal solution is implemented. With this solution, a net savings of 1354.53 $ has been achieved.

Finally, a GA-SA hybrid algorithm has been designed to solve for the optimal solution for this case. Design parameters of the GA-SA algorithm for this case are given in Table (5.42). These parameters are determined empirically. The optimal solution with these parameters is shown in Table (5.43). Fixed and switched capacitors need to be installed at five different places. The solution can be summarized as follows:

1. A 1200 kVar switched capacitor shall be placed at bus # 8. During the light and medium load levels, the capacitor is switched to give 600 kVar only. However, it shall be switched to give 1200 kVar during the peak load level.
2. A 300 kVar fixed capacitor shall be placed at bus # 21.
3. A 1200 kVar fixed capacitor shall be placed at bus # 48.
4. A 900 kVar fixed capacitor shall be placed at bus # 50.
6. A 1200 kVar switched capacitor shall be placed at bus # 61. The capacitor is switched to give 600 kVar, 900 kVar and 1200 kVar during the light, medium and peak load levels respectively.

System conditions with the optimal solution are given in Table (5.44). When compared to the original system without capacitor placement, we have achieved a net savings of 4591.95 $.

Table 5.42 - Test System-1: GA-SA Design Parameters (Case-III)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	3000	0.57	7	0.90	20	20	0.2	5	1.0

Table 5.43 - Test System-1: Optimal Solution Using GA-SA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
8	600	600	1200
21	300	300	300
48	1200	1200	1200
50	900	900	900
61	600	900	1200

Table 5.44 - Test System-1: System Conditions with the Optimal Solution Using GA-SA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.969	0.9471	0.9349
Maximum Bus Voltage (pu)	1.0054	1.0041	1.0030
Maximum THD (%)	2.526	4.599	4.739
Read Power Losses (KW)	38.4292	92.1594	147.9864
Cost of Energy Losses ($)	2305.753	37379.84	8879.183
Total Cost of Energy Losses = 48564.78 $			
Installation Cost of Capacitors = 19400 $			
Total System Cost = 67964.78 $			

5.4 Comparison of the results for test system-1

This section summarizes the simulation results obtained by the heuristic techniques for the three cases.

5.4.1 Test system-1 : comparison of the results for Case-I

A summary of the simulation results obtained by all the heuristic techniques for Case-I is given in Table (5.45). For this case, it is clear that all the heuristic algorithms achieved the same optimal solution.

5.4.2 Test system-1 : comparison of the results for Case-II

For case-II, the best optimal solution is achieved by the GA-SA algorithm. The second best solution is the one obtained by SA followed by the one obtained by TS and finally the one obtained by GA. A summary of the results is provided in Table (5.46). All the solutions are very close to each other.

5.4.3 Test system-1 : comparison of the results for Case-III

For case-III, the optimal solution obtained by the GA-SA algorithm is the best. The second best solution is the one obtained by SA. It is followed by the GA solution and finally the solution obtained by TS. A summary of the results is provided in Table (5.47).

Table 5.45 - Test System-1: Comparison of the results for Case-I

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	21 (300,300,300) 61 (1200,1200,1200)	21 (300,300,300) 61 (1200,1200,1200)	21 (300,300,300) 61 (1200,1200,1200)	21 (300,300,300) 61 (1200,1200,1200)
Cost of Energy Losses	48478.33	48478.33	48478.33	48478.33
Installation Cost of Capacitors	6500	6500	6500	6500
Total System Cost	54978.33	54978.33	54978.33	54978.33
Savings	17028.44	17028.44	17028.44	17028.44

Table 5.46 - Test System-1: Comparison of the results for Case-II

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	12 (0,300,300) 61 (900,900,1200)	12 (600,600,600) 61 (600,900,1200)	21 (300,300,300) 61 (900,1200,1200)	21 (0,300,300) 61 (600,900,1200)
Cost of Energy Losses	47807.47	47449.47	47908.65	47472.95
Installation Cost of Capacitors	6500	7400	6500	6500
Total System Cost	54307.47	54849.47	54408.65	**53972.95**
Savings	17699.3	17157.3	17598.12	**18033.82**

Table 5.47 - Test System-1: Comparison of the results for Case-III

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	8 (600,1200,1200) 21 (0,300,300) 48 (900,1200,1200) 49 (300,300,300) 59 (0,0,300) 61 (900,900,1200)	8 (900,1200,1200) 12 (600,600,600) 48 (300,900,900) 49 (0,900,900) 61 (600,900,1200)	11 (300,300,900) 48 (600,900,900) 50 (900,900,1200) 59 (600,600,600) 61 (900,900,900)	8 (600,600,1200) 21 (300,300,300) 48 (1200,1200,1200) 50 (900,900,900) 61 (600,900,1200)
Cost of Energy Losses	49469.7	51574.98	52702.2	48564.78
Installation Cost of Capacitors	19500	19400	18500	19400
Total System Cost	68969.70	70974.98	71202.20	**67964.78**
Savings	3587.03	1581.75	1354.53	**4591.95**

5.5 Test system-2 & data

Figure (5.2) shows the one line diagram of test system-2. The test system is a 13.8 kV, 12 kVA, 30-bus distribution feeder consisting of one main branch and two laterals containing different number of load buses. Buses 1 to 17 lie on the main branch. The system also contains a loop connecting bus # 18, 19, 20 and 21 to the main branch. Bus # 1 represents the substation feeding the distribution system.

Table (5.48) shows the network data for this system. A feeder segment is modeled by the series combination of its corresponding resistance and reactance.

Loads are represented as power sink where constant values of active power (P) and reactive power (Q) are assumed. Table (5.49) shows the corresponding P and Q for the loads connected to each bus.

Nonlinear loads are included in the formulation of the CPP to study their effect on the optimal solution. For this, some of the buses are assumed to have nonlinear loads. Table (5.50) lists the buses to which nonlinear loads are connected together with the respective nonlinear load percentages.

To account for load variation in the system, three different load levels are considered. They are classified as light, medium and peak. Load duration data assumed for the system are shown in Table (5.51).

Cost figures and other pertinent data given in Table (5.5) are also applicable for this test system.

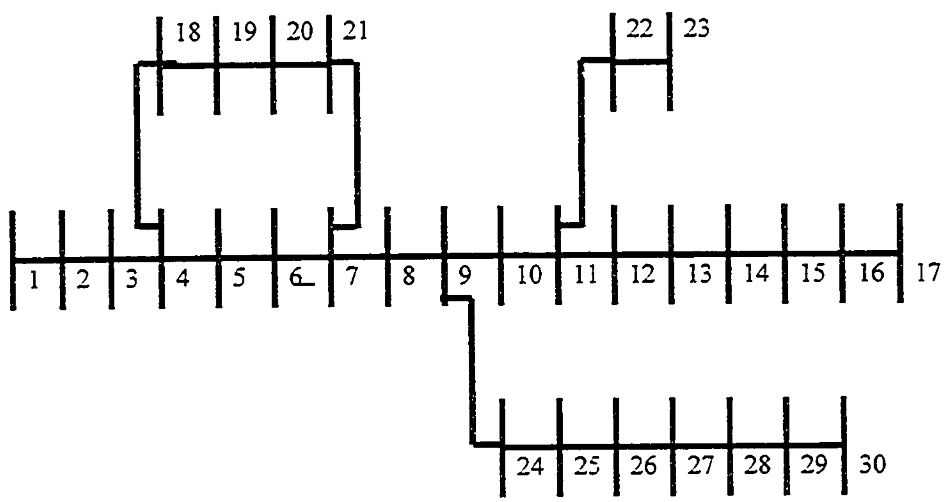


Figure (5.2) : Schematic Diagram of a 30-bus System (Test System-2)

Table 5.48 – Test System-2: Network Data

From	To	R (ohm)	X (ohm)	From	To	R (ohm)	X (ohm)
1	2	0.0005	0.0012	16	17	0.3744	0.1238
2	3	0.0005	0.0012	4	18	0.0047	0.0016
3	4	0.0015	0.0036	18	19	0.3276	0.1083
4	5	0.0251	0.0294	19	20	0.2106	0.0696
5	6	0.3660	0.1864	20	21	0.3416	0.1129
6	7	0.3811	0.1941	21	7	0.0140	0.0046
7	8	0.0922	0.047	11	22	0.1591	0.0526
8	9	0.0439	0.0251	22	23	0.3463	0.1145
9	10	0.819	0.2707	9	24	0.7488	0.2475
10	11	0.1872	0.0619	24	25	0.3089	0.1021
11	12	0.7114	0.2351	25	26	0.1732	0.0572
12	13	1.030	0.340	26	27	0.0044	0.0108
13	14	1.044	0.345	27	28	0.0640	0.1565
14	15	1.058	0.3496	28	29	0.3978	0.1315
15	16	0.1966	0.065	29	30	0.0702	0.0232

Table 5.49 – Test System-2: Load Data

Bus #	P(kW)	Q(kVar)	Bus #	P(kW)	Q(kVar)
1	0	0	16	145.5	130
2	300	280	17	60	35
3	0	0	18	360	335
4	1200	1170	19	1200	1100
5	100	80	20	200	190
6	112.6	105.2	21	114	81
7	400.4	300	22	50.3	30.5
8	75	54	23	80	65
9	130	122	24	28	20
10	280	190	25	1500	1380
11	145	104	26	140	100
12	145	104	27	1114	910
13	80	50.5	28	326	218.6
14	118	115.5	29	426	318.6
15	700	630	30	300	280

Table 5.50 – Test System-2: Buses of Nonlinear Loads

Bus #	w_i (%)
2	40
6	50
15	45
19	30
22	25
25	35
27	45

Table 5.51 – Test System-2: Load Duration Data

	Load Level		
	Peak	Medium	Light
S	1.1	0.85	0.55
Duration (hrs)	1000	6760	1000

As done for test system-1, prior to the application of modern heuristic techniques to solve the CPP for a distribution system, a sensitivity analysis has been carried out to select a subset of candidate buses for capacitor installation. The aim of this analysis is to enhance the efficiency of the solution algorithms without jeopardizing the quality of the final solution obtained. The most sensitive buses, characterized by high sensitivity factors, are selected. Table (5.52) shows the sensitivity factors, obtained from the sensitivity analysis explained in section 3.3, of the network buses. Based on the sensitivity analysis results and other engineering judgements, six buses have been selected. These buses are bus # 4, 11, 15, 19, 25 and 27.

5.6 Test system-2 conditions prior to capacitor placement

Prior to capacitor installation, a load flow program based on Gauss-Seidel iterative method was run to obtain the present system conditions. System conditions are shown in Table (5.53). The table specifies the minimum per-unit bus voltage, maximum per-unit bus voltage, real power losses in kW and the cost of energy losses during all load levels. It is clear from the table that the minimum bus voltage during the peak load level is less than the pre-specified minimum allowable bus voltage. Therefore, capacitors shall be installed to provide the required voltage correction and to reduce the overall energy losses in the system.

System conditions without capacitor placement, if nonlinear loads are considered, are shown in Table (5.54). In comparison with Table (5.53) where all the loads are assumed

Table 5.52 – Test System-2: Sensitivity Factors (SF) of the Buses

Bus #	SF*10^5	Bus #	SF*10^5
1	0.0	16	1.03481
2	0.00711	17	0.01643
3	0.01134	18	0.2121
4	0.03045	19	0.33465
5	0.2776	20	0.52719
6	0.53272	21	0.80087
7	0.61188	22	0.80344
8	0.65093	23	1.10206
9	0.77198	24	1.28486
10	0.79632	25	1.37903
11	0.84644	26	1.38032
12	0.91167	27	1.38565
13	0.97214	28	1.41350
14	1.02698	29	1.41574
15	1.03222	30	0.01090

Table 5.53 – Test System-2: System Conditions prior to Capacitor Placement (Linear loads only)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9618	0.9398	0.9207
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	143.9909	356.2127	616.2427
Cost of Energy Losses ($)	8639.456	144479.90	36974.56
Total Cost of Energy Losses = 190093.90 $			

Table 5.54 – Test System-2: System Conditions prior to Capacitor Placement (Both Linear & non-linear loads)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9623	0.9403	0.9211
Maximum Bus Voltage (pu)	1.0005	1.0005	1.0005
Maximum THD (%)	3.267	3.301	3.335
Real Power Losses (KW)	144.1153	356.5543	616.9293
Cost of Energy Losses ($)	8646.921	144618.4	37015.750
Total Cost of Energy Losses = 190281.10 $			

to be linear, it can be seen that system minimum and maximum bus voltages have increased slightly due to the addition of harmonic voltages in calculating the overall rms bus voltages as given in equation (3.8). In addition, real power losses during all the load levels and hence the total cost of energy losses in the system have increased because of the harmonic currents injected by the nonlinear loads into the system.

Simulation results for this case show that the maximum total harmonic distortion in the system during every load level is below the specified limit of 5%.

5.7 Simulation results for test system-2

The proposed solution methodologies have been implemented in FORTRAN-77. A 133 MHz PC was used to execute the programs. The same cases, which have been studied for test system-1, are also studied here for test system-2.

5.7.1 Test system-2 : simulation results obtained for Case-I

Different solution algorithms based on SA, GA,TS and a hybrid GA-SA algorithm have been designed to find the optimal solution for this case. In this case, only fixed type capacitors can be installed in the system and all the loads are assumed to be linear. Computer programs have been written for these algorithms based on the respective procedures highlighted earlier.

Table (5.55) shows the design parameters of SA algorithm applied to solve for the optimal solution of this case. These parameters are set empirically by trial and error procedure. It shall be noted here that proper selection of these parameters is a very time consuming task. Probably, it is the most difficult part in the design of the algorithm.

Table (5.56) shows the optimal solution obtained by the SA algorithm designed with the parameters in Table (5.55). The solution calls for a 900 kVar fixed capacitor to be installed at bus # 15, a 1200 kVar fixed capacitor to be installed at bus # 25 and a 1200 kVar fixed capacitor to be installed at bus # 27.

System conditions with capacitors placed as per the optimal solution are given in Table (5.57). As expected, capacitors have regulated the system voltages at the peak load level to lie within the upper and lower voltage limits specified in Table (5.5). Also, real power losses have been reduced as a result of capacitor installation. Consequently, the total cost of energy losses has been reduced.

Considering the system cost prior to capacitor placement and the system cost after capacitor placement, it can be concluded that a net savings of 60293.2 $ has been achieved.

Secondly, Table (5.58) shows the design parameters of the GA algorithm applied to obtain the optimal solution of this case. The parameters are as defined earlier. Again, the parameters are set empirically by trial and error procedure. Parameters that have resulted in the best solution were chosen. A genetic algorithm designed based on steady-state replacement usually converges faster than the one designed based on generational replacement. Due to this, steady-state replacement method requires less number of generations before it converges to the optimal solution. With these parameters, the optimal solution obtained is as shown in Table (5.59). This solution is identical to the one obtained by SA where a 900 kVar fixed capacitor is to be installed at bus # 15, a 1200

Table 5.55 – Test System-2: SA Design Parameters (Case-I)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	4000	0.83	6	0.93	80

Table 5.56 – Test System-2: Optimal Solution Using SA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.57 – Test System-2: System Conditions with the Optimal Solution by SA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9745	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	90.237	216.1888	396.6726
Cost of Energy Losses ($)	5414.222	87686.16	23800.36
Total Cost of Energy Losses = 116900.7 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129800.7 $			

Table 5.58 – Test System-2: GA Design Parameters (Case-I)

Parameter	Ps	M_r	G	C_r
Design Value	42	0.13	40	1.0

Table 5.59 – Test System-2: Optimal Solution Using GA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.60 – Test System-2: System Conditions with the Optimal Solution by GA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9745	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	90.237	216.1888	396.6726
Cost of Energy Losses ($)	5414.222	87686.16	23800.36
Total Cost of Energy Losses = 116900.7 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129800.7 $			

kVar fixed capacitor is to be installed at bus # 25 and a 1200 kVar fixed capacitor is to be installed at bus # 27.

Table (5.60) shows the system conditions when capacitor placement is implemented as per the optimal solution. As can be seen from the table, the voltage at the peak load level has been regulated. In addition, energy loss reductions at different load levels have been achieved. The cost of the optimal solution obtained here is the same as the one obtained by SA.

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.61) shows the algorithm design parameters. As in the cases of SA and GA algorithms, parameters of the TS algorithms are set empirically. The optimal solution with these parameters is shown in Table (5.62). The solution is identical to the one obtained by SA and GA. System conditions with the optimal solution are given in Table (5.63) where the same net savings achieved by SA and GA are achieved by TS as well.

Finally, a hybrid algorithm has been designed by combining both GA and SA. The algorithm is referred to as GA-SA algorithm. In this hybrid algorithm, GA is applied first to obtain a fairly good feasible solution. This solution is used as the initial solution for the SA algorithm in its search for the optimal solution.

Design parameters of the GA-SA algorithm for this case are given in Table (5.64). These parameters are determined empirically. An identical solution to those obtained by SA, GA and TS algorithms is obtained here by applying the GA-SA algorithm as shown in Table (5.65). System conditions with the optimal solution are given in Table (5.66).

Table 5.61 – Test System-2: TS Design Parameters (Case-I)

Parameter	T_s	V	I_t
Design Value	7	4	20

Table 5.62 – Test System-2: Optimal Solution Using TS (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.63 – Test System-2: System Conditions with the Optimal Solution by TS (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9745	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	90.237	216.1888	396.6726
Cost of Energy Losses ($)	5414.222	87686.16	23800.36
Total Cost of Energy Losses = 116900.7 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129800.7 $			

Table 5.64 – Test System-2: GA-SA Design Parameters (Case-I)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	6500	0.83	6	0.93	40	17	0.11	4	1.0

Table 5.65 – Test System-2: Optimal Solution Using GA-SA (Case-I)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.66 – Test System-2: System Conditions with the Optimal Solution by GA-SA (Case-I)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9745	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	90.237	216.1888	396.6726
Cost of Energy Losses ($)	5414.222	87686.16	23800.36
Total Cost of Energy Losses = 116900.7 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129800.7 $			

5.7.2 Test system-2 : simulation results obtained for Case-II

In this case, both fixed and switched type capacitors can be installed in the system and all the loads are assumed to be linear. Different solution algorithms based on SA, GA,TS and a hybrid GA-SA algorithm have been designed to find the optimal solution for this case. Computer programs have been written for these algorithms based on the respective procedures highlighted earlier.

Table (5.67) shows the SA design parameters for this case which have been determined empirically. With these parameters, the optimal solution is as shown in Table (5.68). The solution is summarized as follows:

1. A 900 kVar switched capacitor is to be placed at bus # 15. Two banks shall be switched on during the light load level to supply 600 kVar to the system. The third bank shall be switched on during both the medium and peak load levels to supply a total of 900 kVar to the system.
2. A 1200 kVar fixed capacitor needs to be installed at bus # 25.
3. A 1200 kVar fixed capacitor needs to be installed at bus # 27.

Table (5.69) shows the system conditions with capacitors placed according to the optimal solution. It is clear from the table that system voltages have been regulated to lie within the acceptable range. More reductions in the cost of the energy losses during different load levels have been achieved as compared to case-I with fixed capacitors only. A net savings of 60480.4 $ is achieved when this solution is applied.

Table 5.67 – Test System-2: SA Design Parameters (Case-II)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	8000	0.83	6	0.92	80

Table 5.68 – Test System-2: Optimal Solution Using SA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
15	600	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.69 – Test System-2: System Conditions with the Optimal Solution by SA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9715	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Read Power Losses (KW)	87.1171	216.1888	396.6726
Cost of Energy Losses ($)	5227.028	87686.16	23800.36
Total Cost of Energy Losses = 116713.5 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129613.5 $			

Secondly, a GA-based solution algorithm has been designed for this case. Table (5.70) shows the design parameters of the GA algorithm obtained experimentally to get the best results. With these parameters, the optimal solution obtained is as shown in Table (5.71). The solution is summarized as listed below:

1. A 900 kVar fixed capacitor is to be installed at bus # 15.
2. A 1200 kVar switched capacitor is to be installed at bus # 25. Two banks are to be switched on to give 600 kVar during the light load level. During both the medium and peak load levels, four banks are to be switched on to supply 1200 kVar to the system.
3. A 1200 kVar fixed capacitor is to be installed at bus # 27.

Table (5.72) shows the system conditions with capacitors placed as per the optimal solution. As can be seen from the table, required voltage regulation has been attained. With this solution, we have achieved a net savings of 60400.10 $.

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.73) contains the empirically- set algorithm parameters. The optimal solution with these parameters is shown in Table (5.74). The solution is summarized as listed hereunder:

1. A 900 kVar switched capacitor is to be installed at bus # 15. Two banks are to be switched on to give 600 kVar during the light load level. During both the medium and the peak load levels, three banks are to be switched on to supply 900 kVar to the system.
2. A 1200 kVar fixed capacitor is to be installed at bus # 25.
3. A 1200 kVar switched capacitor is to be installed at bus # 27. Three banks are to be switched on to give 900 kVar during the light load level. During both the medium and

Table 5.70 – Test System-2: GA Design Parameters (Case-II)

Parameter	Ps	M_r	G	C_r
Design Value	40	0.17	30	1.0

Table 5.71 – Test System-2: Optimal Solution Using GA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	600	1200	1200
27	1200	1200	1200

Table 5.72 – Test System-2: System Conditions with the Optimal Solution by GA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9734	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	88.4547	216.1888	396.6726
Cost of Energy Losses ($)	5307.281	87686.16	23800.36
Total Cost of Energy Losses = 116793.8 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129693.80 $			

Table 5.73 – Test System-2: TS Design Parameters (Case-II)

Parameter	T_s	V	I_t
Design Value	12	5	40

Table 5.74 – Test System-2: Optimal Solution Using TS (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
15	600	900	900
25	1200	1200	1200
27	900	1200	1200

Table 5.75 – Test System-2: System Conditions with the Optimal Solution by TS (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9711	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Real Power Losses (KW)	85.9331	216.1888	396.6726
Cost of Energy Losses ($)	5155.987	87686.16	23800.36
Total Cost of Energy Losses = 116642.5 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129542.5 $			

the peak load levels, four banks are to be switched on to supply 1200 kVar to the system.

Table (5.75) shows the system conditions when the optimal solution is implemented. The solution obtained by TS achieves a net savings of 60551.4 $.

Finally, a GA-SA hybrid algorithm has been designed to find the optimal solution for this case. Design parameters of the GA-SA algorithm for this case are given in Table (5.76). These parameters are determined empirically. Table (5.77) shows the optimal solution obtained with these parameters. The solution is summarized as follows:

1. A 900 kVar switched capacitor is to be installed at bus # 15. Two banks are to be switched on to give 600 kVar during the light load level. During both the medium and the peak load levels, three banks are to be switched on to supply 900 kVar to the system.
2. A 1200 kVar fixed capacitor is to be installed at bus # 25.
3. A 1200 kVar fixed capacitor is to be installed at bus # 27.

System conditions with the optimal solution are given in Table (5.78). When compared to the original system without capacitor placement, we have achieved a net savings of 60480.4 $.

Table 5.76 – Test System-2: GA-SA Design Parameters (Case-II)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	30000	1.0	5	0.95	100	18	0.13	5	1.0

Table 5.77 – Test System-2: Optimal Solution Using GA-SA (Case-II)

Location	Size (kvar)		
	Light	Medium	Peak
15	600	900	900
25	1200	1200	1200
27	1200	1200	1200

Table 5.78 – Test System-2: System Conditions with the Optimal Solution by GA-SA (Case-II)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9715	0.9532	0.9347
Maximum Bus Voltage (pu)	1.00	1.00	1.00
Read Power Losses (KW)	87.1171	216.1888	396.6726
Cost of Energy Losses ($)	5227.028	87686.16	23800.36
Total Cost of Energy Losses = 116713.5 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 129613.5 $			

5.7.3 Test system-2 : simulation results obtained for Case-III

In this case, both fixed and switched type capacitors can be installed in the system. Also, both linear and nonlinear loads are assumed. Different solution algorithms based on SA, GA, TS and a hybrid GA-SA algorithm have been designed.. Computer programs have been written for these algorithms based on the respective procedures highlighted earlier.

System conditions prior to capacitor placement are shown in Table (5.54). Table (5.79) shows the SA design parameters for this case which have been determined empirically. With these parameters, the optimal solution is as shown in Table (5.80). The solution can be summarized as follows:

1. A 600 kVar switched capacitor shall be placed at bus # 15. During the light load level, the capacitor is switched off. However, it shall be switched on to give 600 kVar during both the medium and the peak load levels.
2. A 1200 kVar fixed capacitor shall be placed at bus # 25.
3. A 1200 kVar fixed capacitor shall be placed at bus # 27.

Table (5.81) shows the system conditions with capacitors placed according to the optimal solution. It is clear from the table that system voltages have been regulated to lie within the acceptable range. However, less reductions in the cost of the energy losses during different load levels have been achieved due to the confinement of harmonic distortion in the problem formulation. Savings of 57490.00 $ have been achieved when this solution is applied.

Secondly, a GA-based solution algorithm has been designed for this case. Table (5.82) shows the design parameters of the GA algorithm obtained experimentally to get

Table 5.79 – Test System-2: SA Design Parameters (Case-III)

Parameter	T_o	A_{ro}	M	C_f	S_c
Design Value	3000	0.86	7	0.90	30

Table 5.80 – Test System-2: Optimal Solution Using SA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
15	0	600	600
25	1200	1200	1200
27	1200	1200	1200

Table 5.81 – Test System-2: System Conditions with the Optimal Solution Using SA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9664	0.9507	0.9320
Maximum Bus Voltage (pu)	1.0010	1.0008	1.0007
Maximum THD (%)	4.609	3.974	3.665
Read Power Losses (KW)	98.3611	222.4496	411.0643
Cost of Energy Losses ($)	5901.669	90225.55	24663.86
Total Cost of Energy Losses = 120791.10 $			
Installation Cost of Capacitors = 12000 $			
Total System Cost = 132791.10 $			

the best results. With these parameters, the optimal solution obtained is as shown in Table (5.83). Fixed and switched capacitors need to be installed as follows:

1. A 900 kVar switched capacitor shall be placed at bus # 15. During the light load level, the capacitor is switched off. However, it shall be switched on to give 900 kVar during both the medium and the peak load levels.
2. A 1200 kVar fixed capacitor shall be placed at bus # 25.
3. A 1200 kVar switched capacitor shall be placed at bus # 27. During the light load level, the capacitor is switched to give 900 kVar. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.

Table (5.84) shows the system conditions with capacitors placed as per the optimal solution. As can be seen from the table, required voltage regulation has been attained. The maximum total harmonic distortion during all the load levels is less than 5% as specified earlier. With this solution, we have achieved a net savings of 59436.6 $.

Thirdly, a TS-based solution algorithm has been designed for this case. Table (5.85) contains the empirically- set algorithm parameters. The optimal solution with these parameters is shown in Table (5.86). Fixed and switched capacitors need to be installed at three different places. The solution is summarized as follows:

1. A 1200 kVar switched capacitor shall be placed at bus # 15. During the light load level, the capacitor is switched to give 600 kVar only. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.
2. A 1200 kVar switched capacitor shall be placed at bus # 25. During the light load level, the capacitor is switched to give 600 kVar only. However, it shall be switched to give 1200 kVar during both the medium and the peak load levels.

Table 5.82 – Test System-2: GA Design Parameters (Case-III)

Parameter	Ps	M_r	G	C_r
Design Value	20	0.17	15	1.0

Table 5.83 – Test System-2: Optimal Solution Using GA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
15	0	900	900
25	1200	1200	1200
27	900	1200	1200

Table 5.84 – Test System-2: System Conditions with the Optimal Solution Using GA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9658	0.9538	0.9352
Maximum Bus Voltage (pu)	1.0008	1.0009	1.0007
Maximum THD (%)	4.198	4.186	3.760
Read Power Losses (KW)	97.9883	217.4152	398.027
Cost of Energy Losses ($)	5879.301	88183.62	23881.62
Total Cost of Energy Losses = 117944.5 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 130844.5 $			

Table 5.85 – Test System-2: TS Design Parameters (Case-III)

Parameter	T_s	V	I_t
Design Value	9	4	30

Table 5.86 – Test System-2: Optimal Solution Using TS (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
15	600	1200	1200
25	600	1200	1200
27	1200	1200	1200

Table 5.87 – Test System-2: System Conditions with the Optimal Solution Using TS (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9715	0.9568	0.9384
Maximum Bus Voltage (pu)	1.0010	1.0010	1.0007
Maximum THD (%)	4.515	4.424	3.863
Read Power Losses (KW)	87.0415	218.326	391.422
Cost of Energy Losses ($)	5222.491	88553.01	23485.32
Total Cost of Energy Losses = 117260.8 $			
Installation Cost of Capacitors = 13800.0 $			
Total System Cost = 131060.80 $			

3. A 1200 kVar fixed capacitor shall be placed at bus # 27.

Table (5.87) shows the system conditions when the optimal solution is implemented. With this solution, a net savings of 59220.3 $ has been achieved.

Finally, a GA-SA hybrid algorithm has been designed to solve for the optimal solution for this case. Design parameters of the GA-SA algorithm for this case are given in Table (5.88). These parameters are determined empirically. The optimal solution with these parameters is shown in Table (5.89). Fixed and switched capacitors need to be installed as follows:

1. A 900 kVar fixed capacitor shall be placed at bus # 15.
2. A 1200 kVar switched capacitor shall be placed at bus # 25. During the light load level, the capacitor is switched to give 300 kVar only. However, it shall be switched to give 1200 kVar during the medium and the peak load levels.
3. A 1200 kVar fixed capacitor shall be placed at bus # 27.

System conditions with the optimal solution are given in Table (5.90). When compared to the original system without capacitor placement, we have achieved a net savings of 59871.1$.

Table 5.88 – Test System-2: GA-SA Design Parameters (Case-III)

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Design Value	10000	0.83	6	0.94	40	15	0.14	3	1.0

Table 5.89 – Test System-2: Optimal Solution Using GA-SA (Case-III)

Location	Size (kvar)		
	Light	Medium	Peak
15	900	900	900
25	300	1200	1200
27	1200	1200	1200

Table 5.90 – Test System-2: System Conditions with the Optimal Solution Using GA-SA (Case-III)

	Load Case		
	Light	Medium	Peak
Minimum Bus Voltage (pu)	0.9734	0.9538	0.9352
Maximum Bus Voltage (pu)	1.0010	1.0009	1.0007
Maximum THD (%)	4.485	4.186	3.76
Read Power Losses (KW)	90.7461	217.4152	398.0270
Cost of Energy Losses ($)	5444.766	88183.62	23881.62
Total Cost of Energy Losses = 117510.00 $			
Installation Cost of Capacitors = 12900 $			
Total System Cost = 130410.0 $			

5.8 Comparison of the results for test system-2

This section summarizes the simulation results obtained by the heuristic techniques for the three cases.

5.8.1 Test system-2 : comparison of the results for Case-I

A summary of the simulation results obtained by all the heuristic techniques for Case-I is given in Table (5.91). For this case, it is clear that all the heuristic algorithms achieved the same optimal solution.

5.8.2 Test system-2 : comparison of the results for Case-II

For case-II, the best optimal solution is achieved by the TS algorithm. The second best solution is the one obtained by SA and the one obtained by GA-SA algorithm. The solution obtained by the GA algorithm for this case has the highest cost. A summary of the results is provided in Table (5.92). All the solutions are very close to each other.

5.8.3 Test system-2 : comparison of the results for Case-III

For case-III, the optimal solution obtained by the GA-SA algorithm is the best. The second best solution is the one obtained by GA. It is followed by the TS solution and finally the solution obtained by SA. A summary of the results is provided in Table (5.93).

Table 5.91 – Test System-2: Comparison of the results for Case-I

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	15 (900,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)	15 (900,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)	15 (900,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)	15 (900,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)
Cost of Energy Losses	116900.7	116900.7	116900.7	116900.7
Installation Cost of Capacitors	12900	12900	12900	12900
Total System Cost	129800.7	129800.7	129800.7	129800.7
Savings	60293.2	60293.2	60293.2	60293.2

Table 5.92 – Test System-2: Comparison of the results for Case-II

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	15 (600,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)	15 (900,900,900) 25 (600,1200,1200) 27 (1200,1200,1200)	15 (600,900,900) 25 (1200,1200,1200) 27 (900,1200,1200)	15 (600,900,900) 25 (1200,1200,1200) 27 (1200,1200,1200)
Cost of Energy Losses	116713.5	116793.8	116642.5	116713.5
Installation Cost of Capacitors	12900	12900	12900	12900
Total System Cost	129613.5	129693.8	**129542.5**	129613.5
Savings	60480.4	60400.1	**60551.4**	60480.4

Table 5.93 – Test System-2: Comparison of the results for Case-III

	Heuristic Method			
	SA	GA	TS	GA-SA
Optimal Solution	15 (0,600,600) 25 (1200,1200,1200) 27 (1200,1200,1200)	15 (0,900,900) 25 (1200,1200,1200) 27 (900,1200,1200)	15 (600,1200,1200) 25 (600,1200,1200) 27 (1200,1200,1200)	15 (900,900,900) 25 (300,1200,1200) 27 (1200,1200,1200)
Cost of Energy Losses	120791.1	117944.5	117260.8	117510
Installation Cost of Capacitors	12000	12900	13800	12900
Total System Cost	132791.1	130844.5	131060.8	**130410.0**
Savings	57490.0	59436.6	59220.3	**59871.1**

Chapter 6

Conclusions and Future Work

This short chapter concludes the thesis and highlights some future work.

6.1 Conclusions

The capacitor placement problem (CPP) in distribution systems has been addressed in this thesis. A new problem formulation has been presented. The objective function consists of two terms, namely the cost of energy losses and the cost of capacitors to be installed. The objective function is a non-differentiable one due to cost of capacitors which is step-like. The capacitor cost is composed of a term to account for the fixed installation cost and another term to account for the capacitor purchase cost.

The aim is to minimize the objective function while satisfying the system's constraints. System's constraints are intended to be realistic in order to have a more reliable solution. They include power flow constraints, load variation, operational constraints i.e. minimum and maximum allowable operating voltages, maximum number of banks to be installed at one location and the maximum total harmonic distortion in the system. Both fixed and switched capacitors can be placed and only standard sizes of capacitor banks are allowed to be installed. Capacitor sizes are treated as discrete variables and therefore optimization of the CPP in distribution systems is a combinatorial one.

The load variation is accounted for by considering three different load levels classified as light, medium and peak load levels with a pre-specified duration for each. When solving the CPP, the number, size, location and the control settings of the capacitors at different load levels shall be determined.

A systematic sensitivity analysis is used to obtain a subset of candidate buses for capacitor installation. The aim of this is to reduce the searching domain by the optimization algorithms applied later.

In this thesis, various heuristic techniques are used as solution tools to find the optimal solution of the CPP in a distribution system. Simulated annealing, genetic algorithm, tabu search and a hybrid algorithm formed from simulated annealing and genetic algorithm have been successfully applied.

A particular attention has been paid to study the effect of nonlinear loads on the optimal solution due to the widespread use of power electronics and solid-state devices that increase the nonlinear portion of distribution loads.

The solution algorithms have been implemented into a software package in FORTRAN-77 and tested on a 69-bus radial distribution system and a 30-bus distribution system containing a loop with promising results. Three different cases were studied as described underneath:

- Case I : With fixed capacitor placement and linear loads
- Case II : With both fixed and switched capacitor placement and linear loads
- Case III : With both fixed and switched capacitor placement and both linear and nonlinear loads

Based on the numerical results obtained, the following conclusions may be drawn:

1. Installation of capacitors has reduced the energy losses in the system. Even when the capacitor installation cost is considered, cost analysis favors capacitor placement.
2. Installation of switched capacitors is more economical than installation of fixed capacitors.
3. The optimal solution is changed substantially due to the inclusion of nonlinear loads in the problem formulation. Possible resonance may take place as a result of capacitor placement. To avoid the resonance condition amplifying the harmonic distortion levels in the system, proper locations and sizes are selected. However, this is done on the expense of the overall savings achieved by capacitor placement. Economical benefits resulting from capacitor installation are negatively affected in the presence of nonlinear loads as compared to the case when all the loads are assumed to be linear.
4. No conclusion can be drawn on which heuristic technique performs the best. However, solutions obtained by the GA-SA hybrid algorithm were the best in most of the cases that have been studied.

6.2 Future Work

The following points are recommended for future extension of the work of this thesis:

1. Distribution systems are inherently unbalanced due to the existence of single-phase, two-phase line segments as well as the single-phase, two-phase and three-phase unbalanced loads. Because of this, consideration of system unbalance is of great significance. It is necessary to solve the power flow on the three-phase basis when solving the CPP in distribution systems. One future work is to extend the problem formulation presented in this thesis to take the system unbalance into consideration.
2. The economic effect of voltage rise resulting from capacitor application may be included in the objective function formulation.
3. One way to reduce the harmonic distortion levels is by installing harmonic filters at particular locations in the system. The cost of these filters, if to be installed, shall be accounted for in the objective function.
4. The problem formulation may be extended to consider the existing voltage regulators in the system.
5. The economical effect of system's capacity release that is defined as the difference between the capacity of the system prior to and after capacitor installation shall be included in the objective function.
6. Distribution transformers shall be accurately modeled and included in the problem formulation since they represent an important harmonic source in the distribution systems.

7. The effect of different load models on the optimal solution shall be investigated since the power sink model is not the most precise one.
8. The load growth in the system may be included by considering a five-year or a ten-year time horizon instead of considering one year only.

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